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ERGONOMICS

HUMAN FACTORS IN WORK, MACHINE CONTROL AND EQUIPMENT DESIGN

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Human Factors in Work, Machine Control and Equipment Design

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Immediate and Low Level Effects of Ionizing Radiations

Edited by A. A. Buzzati-Traverso

Proceedings of The Symposium held at Venice in June 1959 under the joint sponsorship of U.N.E.S.C.O., I.A.E.A. and C.N.R.N. and published as a supplement to the International Journal of Radiation Biology

The effects of low level radiation, from a biological point of view, have received relatively little attention during many meetings on radiobiology held in the past years. The subject, however, appears of primary significance at this time, in view of the widespread use of radiation sources for scientific, medical, industrial and military purposes. For this reason a symposium exclusively devoted to the subject was called for. Thanks to the financial support of U.N.E.S.C.O., I.A.E.A. and the Italian Atomic Energy Agency (C.N.R.N.) and the hospitality of the Fondazione Giorgio Cini, Z. M. Bacq (Belgium), E. Boeri (Italy), A. A. Buzzati-Traverso (Italy) and A. Hollaender (U.S.A.) organized an international symposium on " The Immediate and Low Level Effects of Ionizing Radiations " which has been held at Venice in June 1959. The meeting was attended by some 120 specialists from many countries.

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THE SOCIETY'S LECTURE 1961*

Given at Bristol, 17 April

by THOMAS BEDFORD, O.B.E., D.Sc., Ph.D., M.Inst.Min.E.

RESEARCHES ON THERMAL COMFORT

§ 1. HISTORICAL BACKGROUND

THE purpose of this paper is to describe the progress of research on thermal comfort during the past 40 years, but it is desirable first to give a brief outline of developments up to the end of the first World War.

Crowded rooms tend to be overheated and often ill-ventilated. During the 18th century it seems to have been recognized that the discomfort in such rooms was mainly due to overheating, but ' bad air ' was held partly to blame. Then Lavoisier examined the composition of the air in occupied rooms, and he attributed to carbon dioxide much of the malaise that had generally been attributed to warmth alone (Leblanc 1842). Thereafter excess of carbon dioxide was popularly held responsible for much discomfort.

In 1862, Pettenkofer said that such discomfort was not due merely to warmth or humidity, or to an excess of carbon dioxide or a deficiency of oxygen, but rather to the presence of organic material exhaled from the skin and lungs. In his view carbon dioxide was important only as an index of the concentration of those organic substances. Then began a succession of papers for and against this anthropotoxin theory, and it was not until the years 1892 to 1913 that the results of various researches finally exploded the theory.

Meanwhile evidence had been accumulating that indicated the overwhelming importance of thermal conditions. Hermans (1883) attributed the discomfort to heat and high humidity, and Flugge made confirmatory experiments 20 years later. Leonard Hill and his colleagues (1913, 1914) gave final proof, and they also demonstrated the great importance of air movement in alleviating the discomfort due to hot and moist atmospheres.

Of course, the chilling effect of wind had long been recognized, and as early as 1733 Arbuthnot pointed out that the wind effects this chilling by dispersing the layer of warm, moist air that invests the body. Sir John Leslie (1804) described experiments on the cooling effect of winds, and suggested a ' new and very simple kind of anemometer ' which was to be an alcohol thermometer with a large bulb. The rate of cooling of the thermometer after warming would enable the wind speed to be assessed. Heberden (1826) remarked that the indication of a thermometer was a poor measure of sensible cold, and to estimate this sensible cold he warmed a thermometer to well above 100°F and read its temperature at 10 sec intervals until it cooled to 100°.

It is a matter of common experience that the radiation from the sun or from an open fire exerts a warming influence independently of the air temperature. Tredgold (1824), who was concerned with the warming of buildings, made it clear that indoors with the radiation from an open fire a lower air temperature is required for comfort than when the warming is by simply heating the air.

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*This is the first of a series of lectures which has been instituted by the Ergonomics Research Society to be given annually by a person of distinction in the field of ergonomics. The lecture is known as The Society's Lecture, and it is the intention that it should normally be given at the annual symposium of the Society and published in this Journal.

The chilling effect of cold walls has also long been recognized. Tredgold mentioned, as an advantage of radiant heating, that the objects receiving heat from the fire are always warmer than the air. Then, in 1857, the Commissioners appointed by the General Board of Health to inquire into the warming and ventilation of dwellings put down, as one of the requirements for comfort, that the walls of a room should be at a temperature at least as high as the general temperature of the room, and they mentioned cold walls as a cause of discomfort.

In connection with meteorological observations, Aitken (1887) alluded to the need for an instrument that would show the effects of radiation as tempered by the wind. He used a blackened, hollow, metal sphere 6 in. in diameter, fitted with a thermometer with its bulb at the centre of the sphere. He described a method by which, from the temperature of this black globe and that of a vacuum thermometer, one could obtain a figure indicating the combined effects of solar radiation and of wind. He does not appear to have used his instrument for the study of indoor conditions.

More than 100 years ago much attention was paid to the humidity of the atmosphere. Reid (1844) advocated the addition of moisture to the air during very cold weather. Bernan (1845) said that with air at 74°F a relative humidity of 33 per cent was not unpleasant, but that moister air was breathed from choice ; and the Commissioners of the General Board of Health recommended humidities of 65 to 70 per cent with air temperatures of between 50° and 70°F.

By the outbreak of war in 1914 the importance of the four thermal factors—the temperature, humidity, speed of movement of the air and the radiation from the surroundings—was realized. In 1914, Leonard Hill introduced his kata-thermometer for the purpose of indicating the combined effects of the various thermal factors on the heat-loss from the human body. The thermometer may be used as a dry-bulb or as a wet-bulb instrument. The rate at which the instrument cools is known as the ‘ cooling power ’. Hill advocated the dry kata cooling power as an index of warmth in cool or comfortable conditions, and the wet kata cooling power for conditions such as are met with in hot industries or in the tropics.

In 1916, Hill, Griffith and Flack gave equations expressing the relation between dry kata cooling power and air speed, and since that time the kata thermometer—virtually the ‘ simple kind of anemometer ’ described by Leslie—has been widely used as an anemometer, especially for the measurement of low air speeds.

It had long been known, though perhaps not widely recognized, that comfort depends not only on the general level of warmth but also on the distribution of warmth throughout the occupied space. It had been realized for instance that a room should not be warmed in such a way that the heads of the occupants were overheated while their feet were cold. Tredgold, a pioneer of central heating, remarked in 1824 that steam pipes for warming could be arranged in any manner that was convenient provided they were near the floor. Reid (1844) wrote of the discomfort that arose from great differences between the temperatures of the air around the head and around the feet. The Commissioners of the General Board of Health made measurements of these temperature gradients in rooms, and they recommended that the floor should be at the highest temperature in the room, while the temperature should gradually decrease towards the ceiling.

In the old Debating Chamber of the House of Commons the ventilating air was admitted through gratings in the floor, so that the feet of members were exposed to cool draughts. Giving evidence before a Select Committee of the House of Commons in 1913, Leonard Hill was strongly critical of this arrangement (*vide* House of Commons (Ventilation) 1931), and he later included amongst the desirable conditions to be provided by a system of artificial ventilation, cool heads and warm feet, varying radiant heat, cool and variable breezes, a pleasant relative humidity, and ceaseless variation of cutaneous sensations (Hill 1914). Two years later, the Health of Munition Workers Committee (1916) of which Hill was a member, specified an invigorating atmosphere as being (i) cool rather than hot ; (ii) dry rather than damp ; (iii) diverse in its temperature in different parts and at different times, rather than uniform and monotonous ; and (iv) moving rather than still. The conditions in such an atmosphere would be the opposite of the stuffy and oppressive conditions of crowded and ill-ventilated rooms.

Also giving evidence before the Select Committee in 1913, A. H. Barker said that feelings of stuffiness and oppression are produced when the walls of a room are cold and the air is relatively warm, and that a contrary effect of warmth and freshness is obtained by keeping the walls warm and the air cool.

Thus, by the time of the first World War there was some appreciation of the need for a proper distribution of warmth, and of the influence of the various thermal factors on the pleasantness of the environment, but this recognition was by way of qualitative statements rather than in terms of quantitative relationships.

A difficulty that confronts any student of thermal comfort is the wide diversity of individual requirements, and the literature contains many interesting and amusing examples of this diversity. Commenting on a squabble over the temperature in a theatre in Paris, Morin (1863) remarked that the only way of overcoming such ‘ prejudices and interested oppositions ’ lay in the strict observance of well-made regulations. It was probably such diversity of reaction that led Rubner (1897) to remark that it is a mistake to rely on personal feelings of comfort, for, he said, the feeling of comfort is in many people obtuse, undeveloped and variable.

Probably because of these varying subjective responses to the thermal environment, there was early in the present century, a tendency to place the emphasis on the temperature of the skin as an index of bodily warmth rather than to rely on expressions as to comfort.

§ 2. Developments from 1919 to 1929

As the war drew towards its end in 1918 the Industrial Fatigue Research Board was formed, to continue on a peacetime basis the work which had been so ably begun by H. M. Vernon, Major Greenwood and others under the auspices of the Health of Munition Workers Committee. In the years that followed members of the Board's staff included in their investigations studies of the effects of the thermal environment on comfort, and on efficiency, health and safety, in a variety of industries.

2.1. *Investigations in Factories*

There was some concern about the incidence of tuberculosis in the boot and shoe industry, and an investigation of conditions of work, including atmospheric conditions, in that industry, was undertaken (Hambly and Bedford 1921). The kata-thermometer was an important new instrument and the ' cooling power of the air ' as measured by it was the prime factor to be considered in ventilation. The assessment of working conditions was made in terms of cooling power. But in the earliest days of the investigation the equation of Hill and his colleagues expressing the relation between cooling power and air velocity was used for computing air speeds. Furthermore, in the light of Hill's teaching of the undesirability of hot heads and cold feet, many observations were made of the temperatures at head level and just above the floor, and the results obtained with various methods of heating were compared (Bedford 1923, Bedford and Angus 1923). It was clear that the gradients of air temperature were steeper in factories warmed by hot pipes running overhead than in those warmed by pipes placed near the floor or by the circulation of warmed air.

Early in 1921 the author joined Dr. H. M. Vernon and worked with him until he retired in 1932. Their first joint work was a study of atmospheric conditions in potters' shops, where temperatures were commonly high on account of the heat given off by the drying stoves. Although the investigators found the shops uncomfortably warm, the potters appeared to like the heat, for when the shop temperatures exceeded 70°F with outside temperatures of 50° to 59°F only about 30 or 40 per cent of the available windows were opened (Vernon and Bedford 1922).

A further study of ventilation and heating was carried out in a number of factories where people were engaged in light or relatively light work. The factory workers were questioned as to their sensations of warmth, and their replies were related to the air temperatures and the kata thermometer cooling powers. At some factories it was possible to obtain records of absence due to sickness, and these were related to factory temperatures. Ventilation rates were estimated ; and the effects of various methods of heating and ventilating on thermal gradients and air speeds were studied (Vernon, Bedford and Warner 1926 a).

In relating the workers' responses to factory temperatures no attempt was made to apply modern methods of statistical analysis. The information was tabulated in the form of correlation tables, showing for each sensation of warmth on the 5-point scale used the frequency of occurrence at various temperatures. The mean temperatures at which the different sensations were reported were also tabulated. If further evidence of the diversity of individual requirements was necessary it was provided by those figures. Thus in the ' winter ' observations, made during the heating season, people reported that they were comfortable at temperatures ranging from 53° to 72°F, while in ' summer ' some people were comfortable at temperatures of from 57° to 78°F. At any given temperature there was diversity of response, and at the temperatures which gave the greatest general measure of satisfaction some people were too warm and others too cold. The results obtained in the winter observations are shown in Table 1.

Those observations were concerned with general bodily warmth, but during part of that investigation we also studied the effects of the different thermal factors, including variability of air speed and temperature, on our own impressions of the freshness or otherwise of the environment (Vernon, Bedford and Warner 1926 b). Vernon and Manley (1926) had constructed a hot-wire anemometer with a rapid response to changes in air speed, and a thermopile which responded quickly to changes in air temperature. With those instruments the variability of air speed and of air temperature were measured. Sensory impressions were noted on a 9-point scale ranging from ' very stagnant ' to ' very fresh '.

ble 1. Factory temperatures in relation to sensations of comfort—Winter observations (Vernon, Bedford and Warner 1926 a)

Sensation	Number of observations	Frequency of occurrence of sensation when temperature (°F) was											Mean temperature °F
		Below 47·5	47·5 to 49·9	50 to 52·4	52·5 to 54·9	55 to 57·4	57·5 to 59·9	60 to 62·4	62·5 to 64·9	65 to 67·4	67·5 to 69·9	70 to 72·4	
uch too cold	32	7	1	15	5	—	3	1	—	—	—	—	51.1
oo cold	145	—	3	15	13	33	60	16	5	—	—	—	57·1
omfortable	846	—	—	—	6	25	151	293	245	106	16	4	62·1
oo warm	128	—	—	—	—	—	3	12	49	50	12	2	64·7
uch too warm	15	—	—	—	—	—	—	—	2	1	10	2	68·2

In analysing the results of these observations on freshness the method of correlation was applied. Since the sensations were not quantitative values, correlation ratios, and not correlation coefficients, were calculated. Those ratios suggested (i) that the sensations were more closely related to cooling power than to either temperature or air speed alone ; (ii) that variability of air speed affected sensations to a less extent than did the average speed ; and (iii) that it was doubtful whether such variations of temperature as occurred had any influence on sensations.

2.2. *Effective Temperature*

At the time those factory investigations were in progress work of outstanding importance was undertaken by Houghten and Yagloglou in the United States. In designing air-conditioning equipment it was not enough for the engineer to be told that he should make an allowance for atmospheric humidity or for air speed. He wanted to know how much allowance he should make. Houghten and Yagloglou studied the relations between temperature, humidity and air speed in a long series of experiments on human subjects, and as a result produced their scales of ' Effective Temperature ' (Houghten and Yagloglou 1923, 1924 ; Yagloglou and Miller 1925 ; Yaglou 1926, 1927). The ' basic ' scale of effective temperature applies to people who are stripped to the waist, and the ' normal ' scale to persons wearing normal indoor clothing.

The scales were based on equivalence of comfort. Combinations of temperature, humidity and air speed which felt equally warm to the subjects, who were more or less at rest, were said to be at the same effective temperature, the standard of reference being still and saturated air.

From observations on many subjects comfort zones were established in terms of effective temperature. For American subjects in winter Yaglou (1926) gave a zone of 63° to 71°F effective temperature, and those limits represented conditions in which not less than 50 per cent of the people felt comfortable. For summer conditions Yaglou and Drinker (1928) gave a zone of 67° to 79°F effective temperature, and they apparently took the whole range of effective temperature in which votes of ‘ comfortably cool ’ or ‘ comfortably warm ’ were recorded. Those zones were of great value, in that they gave engineers some guidance as to tolerances, but they have since been subjected to criticism on the ground that they are too wide.

2.3. *Radiant Heat*

The warming of buildings by means of heated ceilings, walls or floors, generally known as panel heating, is the modern equivalent of the Roman hypocaust. The method was introduced by Barker in 1908 when he warmed walls by means of embedded hot-water pipes. After the first World War the method came increasingly into use. Vernon, Vernon and Lorrain-Smith (1928) made a study of this radiant heating in various buildings.

They observed that in rooms heated by ceiling panels vertical gradients of air temperature were virtually non-existent. They made rough estimates of the mean radiant temperature by pointing a radiation thermopile in turn to each of the four walls and to the ceiling and floor. They found that in ventilated rooms with panel heating the mean radiant temperature so estimated was from 3·3° to 5·6°F higher than the air temperature.

2.4. *Measurements of Skin Temperature*

In a study of the heating and ventilation of schools (Vernon, Bedford and Warner 1930) observations were made in some schools with floor heating and in others with mainly convective heating. The radiation thermopile was used for measuring the temperatures of exposed areas of skin.

In some experimental observations such measurements were made on the forehead, the palm, the fingers (palmar surface), and the upper surface of a foot. With an air temperature of 53°F the skin temperatures declined steadily during an exposure of nearly 3 hours, and the subjects felt progressively colder. The temperature of the fingers fell to about 65°F, and that of the foot to about 73°F. At an air temperature of 63°F, with a warmed floor, the subjects felt slightly warmer at the end of the exposure than at the beginning, the temperature of the foot increased slightly to 85°F, while that of the fingers declined slightly to a final level of 84°F.

About 1100 observations were made of the hands of the school children. In one school, when the temperature was only 50°F, the average hand temperature of a group of 11-year-olds was barely 65°F. In some other schools with temperatures averaging 53°F the hand temperatures averaged about 69°F.

§ 3. DEVELOPMENTS FROM 1930 TO 1944

3.1. *Thermal Measurements*

In the study of thermal comfort the measurement of the thermal environment is obviously of great importance. By 1930 there was no difficulty in measuring the temperature and humidity of the air, for the psychrometer in its various forms was well established. There was, however, need for some ready means of assessing radiant heat, and it had been observed that in the presence of appreciable radiant heat the kata-thermometer appeared unreliable as an anemometer.

a. The Kata-thermometer

The standard kata-thermometer had a cooling range of 100° to 95°F, so that when it was used in very warm environments it cooled very slowly, if indeed it did cool. For use as an anemometer in such environments, Hill had introduced a high-temperature kata-thermometer with a cooling range 30° higher, i.e. from 130° to 125°F.

Glass has an emissivity of about 0·9, so that the kata-thermometer was substantially influenced by radiation. However, the equations relating the rate of cooling to the air speed contained no specific term in radiation, so that even if one could express the radiant heat quantitatively the equations did not enable an allowance to be made. It was tacitly assumed that the radiation was equal to that from a surface at air temperature.

In the laboratory the bulbs of kata thermometers were plated with silver, which was then burnished (Bedford and Warner 1933). It was estimated that the emissivity of the silvered bulbs was 0·05 or 0·06, so that the effect of radiant heat was reduced to a negligible amount.

The silvered instruments were calibrated, and equations for the calculation of air speeds were derived and nomograms prepared.

b. Radiant Heat

With the object of finding simple means of assessing the warming effect of the radiation from open fires or from heating panels, Vernon (1930, 1932) experimented with solar radiation thermometers, and with hollow spheres of up to 9 in. diameter, each holding a thermometer with its bulb at the centre of the sphere. Some of these spheres were of pasteboard covered with cloth and others were of copper painted matt black. It was found that to obtain the maximum warming effect a sphere not less than 6 in. in diameter was needed, and that to get a quick response it must be of copper.

Thus Vernon introduced the globe thermometer, which was in fact the instrument earlier referred to by Aitken. Vernon referred to the temperature indicated by the globe thermometer as the ‘ radiation-convection temperature ’, and to excess of that temperature over the air temperature as the ‘ effectual radiation temperature ’. In experiments made indoors he found that his two subjects were comfortable when the globe thermometer registered 62°F whether the air temperature was also 62°F or as low as 49°F. He also noted that the reading of the globe thermometer was much influenced by the movement of air.

In a later study of the thermal comfort of factory workers (Bedford 1936) readings of the globe thermometer were included amongst the instrumental observations that were made systematically. For the direct measurement of radiant heat in that study the Moll radiation thermopile was used. The observations were laborious, for in order to ensure that the sphere surrounding the observation point had been adequately covered it was necessary to take 46 readings and average them. The mean intensity of radiation was expressed in terms of the ‘ mean radiant temperature ’, i.e. that uniform temperature at which a black body would radiate with an intensity equal to the mean observed (Barker 1926).

It seemed that it should be possible to use the globe thermometer observations to obtain something more precise than Vernon’s effectual radiation temperature. Clearly, if the air and the radiating surfaces are at the same temperature the globe thermometer will also register that temperature. If, however, the surrounding surfaces are warmer than the air, when the globe thermometer reaches equilibrium it will be at a temperature somewhere between the temperatures of the air and of the surroundings, and such that the rate at which it gains heat by the radiation exchange with the surroundings (H_r) is equal to the rate at which it loses heat to the air by convection (H_c). There must be a heat balance

$$H_r = -H_c. \tag{1}$$

From well-established constants the radiation equation was well known, and to expand the heat balance equation it was only necessary to measure the heat-loss from a warmed globe over a sufficient range of air speeds so as to derive the convection equation. This was done in the laboratory (Bedford and Warner 1934), and the equation for calculating the mean radiant temperature, in terms of British units, is

$$T_s^4 \times 10^{-9} = T_g^4 \times 10^{-9} + 0{\cdot}1028\, v^{1/2}(t_g - t_a) \tag{2}$$

where

T_s and T_g are the mean radiant temperature and the temperature of the globe thermometer respectively, both expressed in °F Abs. ;
t_g and t_a are the temperatures of the globe thermometer and of the air respectively, in °F ; and
v is the air speed, in ft/min.

The equation involves laborious calculation if many results are to be evaluated, so a nomogram was constructed to reduce labour.

During the factory investigation the globe thermometer was consistently read soon after the direct thermopile measurements had been made, so that a comparison of the mean radiant temperatures obtained (*a*) by means of the thermopile, and (*b*) from the globe thermometer, was a ready way of checking the accuracy of the globe thermometer estimates, although it was realized that small changes, such as the movement of warm objects, might influence the comparison to a minor degree. In 221 pairs of observations the mean difference between pairs of estimates was only 1·2°F.

c. *Equivalent Temperature*

Reference has been made to the scales of effective temperature. Those scales make no allowance for radiation. For studies of radiant heating, whether by incandescent sources or by low-temperature panels, some scale of warmth which would make due allowance for radiant heat was desirable. Vernon’s globe thermometer was not altogether suitable for this purpose. It is true that it is influenced by air speed as well as by the air and mean radiant temperatures, but in circumstances in which the mean radiant temperature is below the air temperature an increase in the air speed, which increases the effect of convection and makes one feel cooler, will raise the globe thermometer temperature to a value more nearly approaching the air temperature.

Dufton (1929) had already devised the eupatheostat as a form of room thermostat which made allowance for radiation. Later, he introduced the eupatheoscope for the measurement of what was called ‘ equivalent temperature ’ (Dufton 1932). This instrument was a hollow cylinder 22 in. high and 7½ in. in diameter. It was heated electrically, the heating being controlled by an internal thermostat which was set at 78°F. The temperature of the external black surface varied over a few degrees according to the temperature of the environment, but in a uniform enclosure with still air at 65°F the surface temperature was 75°F, which is about the average surface temperature of a clother person in similar surroundings. The heat loss, and therefore the heat input, varied with the thermal environment. The reading of the instrument depended on the heat input and was observed on the stem of a thermometer scaled in equivalent temperature.

In the light of later observations on the surface temperatures of clothed persons the instrument was redesigned to make its surface temperature more strictly comparable with that of a clothed person (Dufton 1936). The equivalent temperature is referred back to the standard conditions of a uniform enclosure of still air.

When any index of warmth which takes into account two or more thermal factors is used it is always desirable to have information about the separate factors. Such knowledge will enable one to decide in which direction to seek a remedy if, say, the equivalent temperature is too high or too low. The desirability of recording measurements of the individual thermal factors was emphasized by the Housing Commission of the League of Nations Health Organization (1937), but Dufton never published any equation expressing equivalent temperature in terms of the three variables, air speed, air temperature and mean radiant temperature.

3.2. *Studies of Thermal Comfort*

a. In Great Britain

With the more widespread use of radiant heating the need for further research on thermal comfort became apparent, and in 1933 the author undertook an investigation amongst factory workers engaged in sedentary or very light work (Bedford 1936). All the observations were made during the heating season, so that the findings relate to winter conditions.

One objective was to assess the relative effects of the individual thermal factors on personal feelings of warmth. Another was to ascertain which of the available scales of warmth was most closely related to those sensations. A further aim was to ascertain the optimum level of warmth for persons engaged in light work, and to find what range of warmth should be regarded as the comfort zone. Also, since the temperature of the skin had been used as an index of bodily warmth it was decided to study the relation of skin temperature to the thermal environment and to comfort.

At each observation position instrumental measurements of the environment were made, while the workers in the immediate vicinity were questioned as to their thermal comfort. Then measurements were made of the temperature of the skin (*a*) on the forehead, (*b*) on the palm of one hand, and (*c*) on the inner aspect of one foot just below the ankle ; and measurements were also made of the surface temperature of the clothed body. The air temperatures ranged from 50° to 76°F.

Each worker was questioned individually, and the responses, commonly referred to as ' comfort votes ', were classified into 7 groups :—

Sensation of warmth	*Numerical scale*
Much too warm	1
Too warm	2
Comfortably warm	3
Comfortable	4
Comfortably cool	5
Too cool	6
Much too cool	7

' Comfortably warm ' and ' comfortably cool ' signified that the subject was not uncomfortable but would have preferred slightly cooler or slightly warmer conditions.

(i) *Statistical method.* Reference has been made earlier to the use of correlation *ratios* in examining the closeness of association between sensations and environmental factors. Such ratios are of very restricted value. They indicate the degree of variability of the temperature or other thermal measurement at which the various sensations were reported, but they give no indication of the linearity of the relation between the two variables. Furthermore, the treatment makes the sensation the independent variable, and the thermal measurement the dependent variable. But clearly, the point of interest is the sensory response under given environmental conditions. One wants to know what will be the response of the average person, and if sensation is treated as the independent variable misleading conclusions may be reached. Consider, for example, the figures given earlier in Table 1. The average temperature at which the sensation ' too cold ' was reported was 57·1°F, but in the 58 observations made at temperatures of 55° to 57·4°F 25 people were ' comfortable ', and none was ' much too cold '. It was at temperatures from 52·5 to 54·9°F that the average response was approximately ' too cold '. Similarly, the average temperature at which people were ' too warm ' was 64·7°F, but at temperatures of 65°F or over 62 per cent of the people were ' comfortable '.

Such results always arise when the correlation between two variables is imperfect and there is much scatter. Thus, if for the observations in Table 1 we assign arbitrary values of 1 to 5 to the sensations, so assuming that the steps in the scale represent equal intervals of sensation, we can calculate a correlation *coefficient* and derive equations for the regressions of sensation on temperature and of temperature on sensation.

Figure 1 shows the results of such calculations. The coefficient of correlation (r) of temperature and sensation of warmth was 0·69, a relatively high value in view of the diversity of response that one may expect. Putting y for the arbitrary value of sensation, and x for the temperature in °F, the regression equation for sensation on temperature, in which expression sensation is expressed as dependent on temperature, is :

$$y=0{\cdot}115\times-4{\cdot}13 \tag{3}$$

and that for temperature on sensation is :—

$$x=4{\cdot}14y+49{\cdot}4. \tag{4}$$

The regression lines are shown in Fig. 1. The firm line is drawn from eqn. (3), and the broken line from eqn. (4). The points marked by crosses represent the mean sensation values at various intervals of temperature, and encircled dots the mean temperatures at which various sensations were reported.

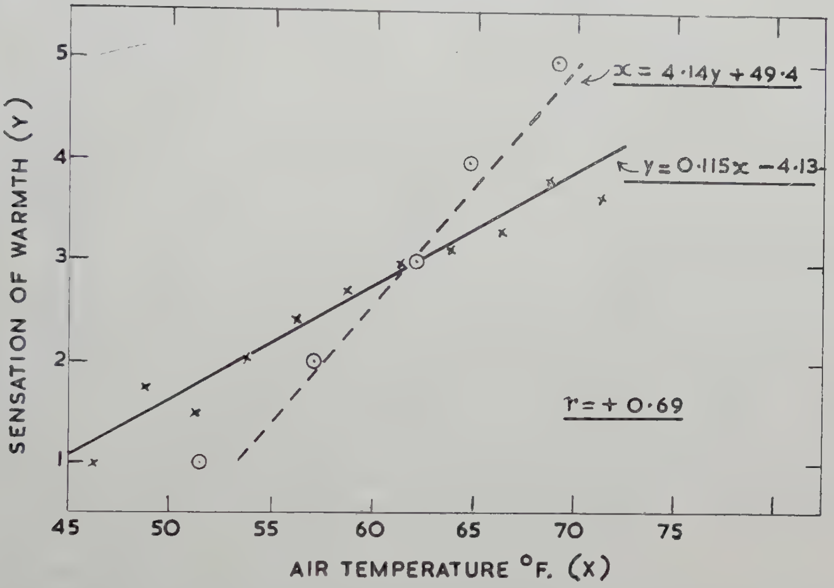

Figure 1. Sensations of warmth in relation to Factory Temperatures (data of Vernon, Bedford and Warner 1926 a).

In dealing with the new (1936) data it was decided to treat the numbers assigned to the scale of sensations as though they actually measured the sensations on a linear scale, and to calculate correlation coefficients. The question arose whether a more reasonable scale could be constructed by assuming a normal distribution of sensations of warmth. This point was examined, and many calculations were made using such a scale, but it was found that the results did not significantly affect any of the conclusions that were reached by using the simple scale that has been set out.

(ii) *Correlation of comfort votes with indices of warmth.* The coefficients of correlation between the 2571 comfort votes and various indices of warmth, and their probable errors, are shown in Table 2.

Table 2. Correlation between comfort votes and indices of warmth

Comfort votes correlated with	Correlation coefficient (r), and *p.e.*
Equivalent temperature	$-0{\cdot}52\pm0{\cdot}01$
Globe thermometer reading	$-0{\cdot}51\pm0{\cdot}01$
Effective temperature	$-0{\cdot}48\pm0{\cdot}01$
Air temperature	$-0{\cdot}48\pm0{\cdot}01$
Dry kata-thermometer cooling power	$+0{\cdot}43\pm0{\cdot}01$

The differences between the first four coefficients are not statistically significant, but each of them is significantly higher than the fifth. Equivalent temperature gave the highest correlation with comfort votes, and it is reasonable to expect that if there had been a greater range of air speeds, or greater disparities between air temperature and mean radiant temperature than were encountered, it might have shown to greater advantage. Within the range of the observations the simple globe thermometer reading was a good index.

Effective temperature was no better than air temperature. It makes no specific allowance for radiant heat, and at moderate temperatures changes in humidity have little effect on feelings of warmth. As an index of warmth the dry kata-thermometer cooling power was definitely inferior to the air temperature.

When regression diagrams were plotted it was clear that the average comfort vote was linked with each of the indices of warmth by a substantially linear relationship, but at any level of warmth the comfort votes varied considerably.

The average temperature in these observations was almost exactly the temperature at which the average comfort vote was ‘ comfortable ’, and the standard error of estimation of comfort votes from air temperature was only about 12 per cent less than the standard deviation of all the comfort votes. For estimates from equivalent temperature the error was 14·5 per cent less. Thus, although the average comfort vote for a large group of people can be estimated from the regression equations, such equations are of no practical value for predicting the comfort votes of individuals.

(iii) *The comfort zone.* From these observations it appears that the optimal conditions for persons doing light work in British factories, i.e. those conditions corresponding with an average vote of ‘ comfortable ’, were :—

Equivalent temperature	62°F.
Globe thermometer temperature	65°F.
Air temperature	65°F.
Effective temperature	61°F.

If as the limits of the comfort zone one took those conditions which corresponded with average votes of ‘ comfortably cool ’ and ‘ comfortably warm ’ the zone appeared to be too wide. In terms of air temperature the limits were 55·8°F and 73·7°F. Scrutiny of the figures showed that within the range of conditions in which not less than 70 per cent of people were ‘ comfortable ’ at least 86 per cent of comfort votes ranged from ‘ comfortably cool ’ to ‘ comfortably warm ’, so that not more than 14 per cent experienced actual discomfort. On that basis the comfort zones recommended were :—

Index of warmth	Comfort zone (°F.)
Equivalent temperature	58–66
Globe thermometer temperature	62–68
Air temperature	60–68
Effective temperature	57–63

(iv) *The effects of the separate thermal factors.* The comfort votes were correlated with air temperature, mean radiant temperature, and the absolute humidity of the air expressed as the partial pressure of water vapour. The effect of air speed on the convective heat loss depends on the difference between the surface temperature of the body and that of the air, as well as on the air speed. Over the range of the observations that temperature difference was directly proportional to the difference between 100°F and the air temperature, and from earlier work it appeared that the convective exchange was closely related to the square root of the air speed. Therefore, in order to allow for the effects of convection the comfort votes were also correlated with values of the expression $v^{1/2}(100-t_a)$ where v is the air speed and t_a is the air temperature.

The partial correlation coefficients are shown in Table 3.

Table 3. Partial correlation of comfort votes with different warmth factors

Comfort votes correlated with	Held constant	Partial correlation coefficient
Air temperature (t_a)	t_w, f, and $v^{1/2}(100-t_a)$	$-0{\cdot}16 \pm 0{\cdot}01$
Mean radiant temperature, (t_w)	t_a, f, and $v^{1/2}100-t_a)$	$-0{\cdot}17 \pm 0{\cdot}01$
Vapour pressure (f)	t_a, t_w, and $v^{1/2}(100-t_a)$	$-0{\cdot}05 \pm 0{\cdot}01$
$v^{1/2}(100-t_a)$	t_a, t_w, and f	$+0{\cdot}08 \pm 0{\cdot}01$

The partial correlation coefficients though small were all statistically significant. The partial regression equation calculated from these coefficients is :—

$$S=11{\cdot}16-0{\cdot}0556t_a-0{\cdot}0538t_w-0{\cdot}0372f+0{\cdot}0372f+0{\cdot}00144v^{1/2}(100-t_a) \qquad (5)$$

where S is the comfort vote (‘ comfortable ’$=4$), the temperatures are in °F, the vapour pressure in mm of mercury, and the air speed in ft/min.

The total correlation (R) for comfort votes with the combination of four variables is 0·51, a value virtually identical with the zero-order coefficient for comfort votes with equivalent temperature.

At the temperatures encountered in this work the effect of atmospheric humidity was small. In calm air, with a speed of only 16 ft/min, at a temperature of 70°F a change of 50 per cent in the relative humidity was equivalent to a change of 3°F in the temperature of the enclosure (air and walls), while at 60°F it was equivalent to a change of only 2·1° in the enclosure temperature.

(v) *A scale of equivalent warmth.* It was recommended by the Inter-Departmental Committee on Terminology, etc., in Heating and Ventilating Research (1931) that if the term ‘ warmth ’ were invested with a scientific meaning it should connote the proper assessment of all the thermal factors which induce human comfort ; and that the term ‘ equivalent warmth ’ should be attached to measurements of warmth scaled by reference to standard conditions. On the basis of eqn. (5) a provisional scale of equivalent warmth was constructed. It was hoped later to extend it to cover warmer conditions than those which have been described, but the work was never carried out, and in the light of subsequent research it seems unnecessary.

(vi) *An equation for equivalent temperature.* If the small effects of humidity are ignored the partial regression of comfort votes on the remaining environmental factors becomes :—

$$S=10{\cdot}89-0{\cdot}0574t_a-0{\cdot}0525t_w+0{\cdot}00162v^{1/2}(100-t_a) \qquad (6)$$

From this relation an equation is readily derived which expresses the equivalent temperature. Scaled back to the standard conditions of an enclosure with perfectly still air in which the air and surroundings are at the same temperature it is :—

$$\text{Equivalent temperature} = 0{\cdot}522t_a + 0{\cdot}478t_w - 0{\cdot}0147v^{1/2}(100 - t_a) \qquad (7)$$

(vii) *Comfort and skin temperature.* Ward (1930) recorded the comfort votes of herself and of four other subjects, and at the same time measured their skin temperatures on various sites. Comfort votes were most closely associated with the temperatures measured over the carotid artery and on the forehead, correlation coefficients of the order of 0·9 being obtained. Such high correlations led Ward to conclude that the temperature of the skin could be used as an index of subjective sensations of warmth.

Ward's and other studies of the relation between thermal sensations and skin temperatures were carried out on small groups of subjects. From a series of observations on a single subject it may be possible to estimate that person's feeling of warmth from a knowledge of his skin temperature with considerable accuracy, but it does not follow that from observations on a large population it will be possible to estimate the feeling of warmth of a given individual with any useful degree of accuracy.

In the study of factory workers about 2500 sets of observations of skin temperature were made. The correlation coefficients for comfort votes and skin temperatures measured on the forehead, hand and foot were respectively $-0{\cdot}23$, $-0{\cdot}36$, and $-0{\cdot}33$. With a given skin temperature on a particular site there was much variation in the temperatures on the other sites.

When air temperature was held constant there remained small, but significant, correlations between comfort votes and the skin temperatures on the various sites. At a given air temperature those people with the cooler skins tended to feel cooler than those whose skins were warmer.

The zero order coefficients of the correlation between comfort votes and skin temperature were all significantly lower than the correlations between comfort votes and the warmth of the environment. Even when the partial correlations of comfort votes with the three skin temperatures were calculated the total correlation (R) of comfort votes with skin temperature was only 0·44, which is lower than the correlation of comfort with the simple air temperature. If from measurements of a person's skin temperature on the three sites one estimated that he was exactly comfortable he might be feeling too cool or too warm. The comfort of the individuals comprising a group could be predicted with slightly greater accuracy by estimating the average comfort vote from knowledge of the room temperature and assuming that all felt equally warm, than by estimating the state of warmth of each individual from measurements of his skin temperature.

More recently, in a study carried out in the United States, it has been found that comfort votes are slightly more closely related to the effective temperature than to the mean skin temperatures of the individuals (Glickman, Inouye, Keeton and Fahnestock 1950).

b. In the United States

Important studies were made by Winslow and his colleagues at the John B. Pierce Laboratory of Hygiene at New Haven, Connecticut. These were concerned primarily with the thermal exchanges between the human body and its surroundings, but the comfort of the experimental subjects was taken into account. Comfort was expressed on a scale of pleasantness, and in these experiments, where many observations were made on a small number of subjects, there was a close relation between pleasantness and the mean temperature of the skin. Whether the subject was nude or clothed, discomfort occurred if the skin temperature exceeded 34°C (93·2°F) or fell below 32°C (89·6°F) (Winslow, Herrington and Gagge 1937 a).

Winslow, Herrington and Gagge (1937 b) also introduced an index of warmth which they designated 'operative temperature'. This index takes no account of atmospheric humidity, and is based on the radiation and convection constants of the human body.

In most of the experiments on which operative temperature was based the air speed was low—commonly about 15 ft/min. In such calm conditions the coefficients used with operative temperature are very similar to those of the globe thermometer.

No special scale of operative temperature for clothed persons has been advanced, but if an allowance for clothing is made it appears that operative temperatures so calculated agree fairly closely with equivalent temperatures (Bedford 1954).

3.3. *Pleasant and Stimulating Environments*

Reference has been made to the earlier observations on freshness, and to the fact that the only statistical treatment of them was the calculation of correlation ratios. Some further information was desired, and as a first step it was decided to re-examine the results of the old observations, and method of partial correlation was applied (Bedford and Warner 1939).

Observations had been made in summer and in winter. The mean temperatures were 71°F in summer and 61°F in winter, and the corresponding mean air speeds were 45 and 30 ft/min. The variability of air speed was derived from observations in which the speed was measured at 2- or $2\frac{1}{2}$-sec intervals over a period of 5 min, and the mean variation was expressed as a percentage of the average speed.

a. Air Movement and Temperature

The numerical values assigned to the impressions of freshness were correlated with mean air speed and with temperature. The partial regression coefficients showed that a given change of air speed had more effect on freshness in summer than in winter. In the winter observations an increase of speed of about 40 ft/min increased the feeling of freshness by one unit on the scale, whereas in summer such a change was associated with an increase of only 20 ft/min in the speed. The invigorating effect of air movement was more noticeable at high temperatures than at low ones, whereas a given change in speed has a greater effect on sensations of warmth when the temperature is low than when it is high.

In the summer observations, when the air temperature and mean speed were both held constant there was a highly significant partial correlation between freshness and variability of speed ($r = 0{\cdot}43 + 0{\cdot}08$). With the same air temperature and average speed an increase of about 14 per cent in the mean variation of speed was accompanied by an increase in freshness equal to one unit on the scale. In the winter observations the residual correlation between freshness and variability of speed was not significant.

The variability of temperature was measured only in the winter observations, and in 73 per cent of those observations the mean variation was less than 0·4°F. These slight variations had no detectable effect on impressions of freshness when the other factors were held constant.

b. *Humidity*

At ordinary room temperatures atmospheric humidity has but little effect on sensations of warmth. It has a greater effect on impressions of freshness. With air temperature and average speed held constant there was, in the winter observations, a significant partial correlation between freshness impressions and relative humidity ($r = -0, 24 \pm 0{\cdot}08$) indicating that a humid atmosphere tends to be less stimulating than a dry one.

From the regression constants it appears that at a temperature of 61°F a rise of $8\frac{1}{2}$ per cent in the relative humidity would be equivalent to a rise of 1°F in the air temperature, whereas with respect to sensations of warmth a change of 24 per cent in the relative humidity would be required to compensate for an alteration of 1°F in the temperature.

c. *Radiant Heat*

In the course of field investigations feelings of stuffiness were experienced from time to time when no explanation could be suggested other than the fact that the mean radiant temperature was 6°F or more below the air temperature (Bedford and Warner 1939). It was not until after 1945 that experimental evidence on this presumed effect of radiation was procured.

§ 4. DEVELOPMENTS SINCE 1945

During the war years increased attention was necessarily paid to the physiological effects of high temperatures. This work was mainly concerned with men's ability to endure extreme conditions, with the assessment of heat stress, and with the effects of heat on performance. It does not fall within the scope of this review.

4.1. *Corrected Effective Temperature*

In calculating effective temperatures, Vernon and Warner (1932) made allowance for radiation by using the reading of the globe thermometer instead of the dry-bulb temperature, and by making an adjustment to the observed wet-bulb temperature to allow for the difference between the globe and dry-bulb temperatures.

When, during the war, there was urgent need for a scale of warmth that would make allowance for radiant heat, the use of the globe thermometer reading in place of the air temperature was proposed, but without any adjustment of the wet-bulb temperature. The values thus obtained became known as ‘ corrected effective temperature ’ (Bedford 1946).

It has been confirmed, especially by the work carried out at the Royal Naval Tropical Research Unit at Singapore, that the corrected effective temperature makes adequate allowance for radiation.

The effective temperature scales have been criticized on grounds other than the neglect of radiation (cf. Smith 1955), but those criticisms refer to conditions well outside the range of comfort.

4.2. *Comfort Zones*

In the tropics physiological acclimatization to heat presumably has some effect on comfort, and there is little doubt that inurement to heat also plays its part. Thus, referring to the hot, arid zones of Australia, Drysdale (1950) concluded that while people may prefer an air temperature of 75°F they become accustomed to a feeling of heat and do not feel really uncomfortable until the temperature approaches 84°F. In the humid conditions of Singapore, Ellis (1953) found that for Europeans the limiting effective temperatures for reasonable comfort were 72° to 79°F, and it is interesting to note that the upper limit represents an air temperature virtually identical with Drysdale's figure of 84°F.

The criteria on which the limits of comfort zones are decided are of basic importance. Leopold (1947) referred to the close tolerance that may be necessary to satisfy a group of people, even though the individual tolerances may be wide. A few years ago the author had a clear example of the need for a close tolerance. On account of complaints by Members of Parliament he was asked to examine conditions in the rebuilt House of Commons. From a record of complaints it was evident that whatever the tolerances of individual Members it was necessary to control the temperature within very narrow limits. Accordingly it was recommended that during ordinary sittings, when the House is not densely occupied, the temperature should be maintained at 67° to 68°F, that during late sittings the temperature should be 1° or 2° higher, and that when the House is crowded the temperature should be reduced by 2° or 3°F. With this strict regulation of temperature complaints became less frequent.

4.3. *Freshness*

a. Air Movement

Turner (1955), studying radiative and convective stimuli of threshold intensity, examined the effects of mild currents of air impinging on the face. In air at 66°F a sudden increase of speed from the basic level of 12 ft/min to 30 ft/min was enough to produce a just-perceptible feeling of coolness. From the correlations of Bedford and Warner (1939) it was calculated that at that temperature rapid and random alternations of speeds of 12 and 30 ft/min would have caused the air to feel rather fresh to their subjects, whereas alternations of half that amplitude would have left the subjects with a preference for more stimulating conditions.

b. Warm Walls

Munro and Chrenko (1949) studied the reactions of 145 persons, each of whom was exposed three times to a given equivalent temperature (60°, 65° or 70°F), once with the boundary surfaces of the room at air temperature, once with the surface temperature 5° below air temperature, and once with it 3° above air temperature.

Of those who were exposed to the comfortable equivalent temperatures of 65° and 70°F, 84 per cent found the warm-wall situation more pleasant than the cold-wall one. The warm-wall condition felt distinctly fresher than either of the others, and in the cold-wall condition they felt rather less fresh than when walls and air were at the same temperature. Here was clear experimental evidence of the importance of radiation in relation to the pleasantness of an environment, and a demonstration of the value of good thermal insulation of buildings.

4.4 *The Distribution of Warmth*

a. Temperature Gradients

In some factories the author and his colleagues have found that the air at head level tends to be 10°F or more warmer than that near the floor, and with such gradients feelings of stuffiness have been experienced and conditions have been unpleasant. On the other hand, when the gradient over the height of a standing man has been no more than 2° or 3° the conditions have been pleasant. From general observation over many years, it is the author's conclusion that the gradient of temperature from floor to head level should not exceed 5°F, and should preferably be less.

b. Heated Ceilings

When a room is warmed by means of a heated ceiling there is not usually any appreciable gradient of air temperature over the height of a man. Nevertheless there is a thermal gradient in that the head is subjected to the radiation from the heated ceiling. From experiments carried out on many subjects, Chrenko (1953) found that little, if any, discomfort will arise provided the increase in the mean radiant temperature at head level due to the heated ceiling does not exceed 4°F. With more intense radiation, whether due to the heating panels being hotter or of greater area, considerable discomfort may be experienced. One may find the radiation unpleasant even though the head does not feel to be over warm.

c. Heated Floors

In recent years floor heating has been used increasingly, and from time to time views have been expressed as to the maximum desirable temperature of the surface of a heated floor, but with little or no experimental evidence.

From experiments, Herrington and Lorenzi (1949) concluded that floor temperatures above 75°F were physiologically undesirable, and that with floor temperatures above 80°F there were clearly noticeable effects of the temperature of the feet.

Later, Chrenko (1957) reported experiments on men and women who wore their normal footwear, and who in different experiments sat with their feet on a heated floor or walked about on it. The air temperature ranged between 58° and 76°F in different experiments, and averaged 68°F over the series. When the subjects walked, and thus made firmer contact with the floor, the effect of floor temperature on the temperature of the soles of their feet was greater than when they sat. The skin temperature of the feet was influenced by the air temperature as well as by the floor temperature. Some subjects felt local discomfort when the skin temperature on the sole exceeded 86°F, and when that temperature reached 93½°F discomfort was experienced in 50 per cent of the experiments. The highest floor temperature at which no discomfort was experienced was 77°F.

4.5. *Statistical Methods*

The value of the method of correlation in comfort studies has been discussed and illustrated. Another valuable method which can be applied when dealing with quantal responses is that of probit analysis. During the past decade Chrenko (1953, 1955) has used probit analysis with great profit.

5. CONCLUSION

This outline of researches on thermal comfort has necessarily been selective, but it is hoped that it has shown the way in which methods have been developed and knowledge obtained.

Much of the work carried out for many years past has been directed to the quantitative evaluation of effects that have long been appreciated qualitatively.

Instruments are now available with which the various factors that make up the thermal environment can be assessed. They are readily portable, and convenient for use in field investigations.

The relative effects of the individual thermal factors on sensations of warmth are known, and scales of warmth which facilitate the comparison of indoor environments are available and have been much used. There is still argument as to the relative merits of some of these scales, but as they now stand they are of great practical value. Nevertheless, it should be reiterated that when such scales are used measurements of the individual thermal factors should always be recorded. Furthermore, in stating desirable conditions the limiting values for the separate factors should be specified, for the optimum level of general warmth will not be conducive to comfort if it is achieved with, for instance, a saturated atmosphere or an excessive wind speed.

From past studies it is now possible to prescribe for various situations ‘ comfort zones ’ which are likely to give satisfaction to most of the people concerned.

A good deal is now known about the influence of the different factors on the pleasantness or otherwise of the thermal environment. Research studies have shown the beneficial effects of variable, gentle air movement and of mild radiant heat, and they have shown that at ordinary room temperatures a change in the relative humidity of the air which is negligible from the standpoint of body heat-loss may have a significant effect on one’s impression of freshness.

It has long been realized that the distribution of warmth in a room may have a considerable effect on comfort. The results of recent work enable one to specify limiting values for some variations in local warmth. Such limiting values as have been mentioned with respect to vertical gradients of air temperature, to radiation from heated ceilings, or to the surface temperatures of warmed floors, are valuable criteria by which the merits or otherwise of a heating or air-conditioning installation may be judged.

It is not intended to imply that knowledge regarding thermal comfort, even in indoor environments, is complete. For example, more knowledge is needed about the effects of the quality of the radiation from sources of heat ; and new developments in the heating and air conditioning of buildings will doubtless bring new problems.

Concerning outdoor environments the outstanding need is for further knowledge of the heat exchanges by a man exposed to solar radiation, and for instrumental methods of assessing the radiation out of doors.

Measurements of direct solar radiation, and of radiation from the sky and from the terrain, have been made, but there is need for a method of expressing the radiation exposure in a single figure similar to the mean radiant temperature used in connection with indoor environments. This problem is the subject of present research (Underwood and Ward 1961).

Meanwhile, as a single-figure index of the total heat exposure of a man out of doors the so-called wet bulb—globe temperature introduced by the late Professor Yaglou has much to commend it. It requires only the simple measurements of wet-bulb and globe-thermometer temperatures, and is readily computed ; and it is probably a reasonably good index of warmth.

In this paper Dr. Bedford discusses research on thermal comfort. He is concerned mainly with a search for methods of measuring the state of a thermal environment which accord with subjective scales of comfort. Two impressions of comfort, warmth and freshness, are considered separately and recommendations are made on the values of environmental parameters likely to produce optimum comfort in the maximum proportion of a population sample.

The experiments emphasize the importance of a large variance of air movement and a correctly chosen humidity as less obvious factors in thermal comfort. Wall temperatures which are lower than the air temperature of a room have been traced as a frequent source of stuffiness. Discomfort is also felt if the air temperature at head level exceeds that of floor level by 5°F.

Measurements on the skin temperature of 2500 factory workers indicates that although skin temperature is closely correlated with the sensation of warmth in an individual it is too inconsistent to be used as an index of warmth in a large population.

Dans cette étude Dr. Bedford examine la recherche concernant le confort thermal. Il traite notamment la recherche ayant le bût de trouver des méthodes mesurant l'état d'un entourage thermal qui s'accorde aux mesures subjectives de confort. Deux impressions de comfort—la chaleur et la fraîcheur—ont été examinées séparément, et des recommendations ont été faites concernant les valeurs des paramètres d'entourage qui sont susceptibles de produire du confort maximum dans une proportion maximum d'un échantillon de la population.

Les expériences soulignent l'importance d'une variance considérable d'un mouvement de l'air et d'une humidité choisie d'une façon correcte étant des facteurs moins évidents relatif au confort thermal. Des températures des murs qui sont plus basses que la température ambiante d'une chambre ont été constatées d'être une source importante d'un état étouffant. On se sent aussi peu confortable si la température de l'air au niveau de la tête est à l'excès de celle-ci au niveau par terre de 5°F.

Des mesurages de la température de la peau de 2500 ouvriers industriels suggèrent que, bien que la temperature de la peau ait une corrélation étroite avec la sensation de la chaleur dans un individu, ils ne sont pas suffisamment consistentes afin d'être utilisées comme un indice pour la chaleur dans une population importante.

In dieser Abhandlung bespricht Herr Dr. Bedford die Erforschung thermaler Toleranz. Er befasst sich hauptsächlich mit einer Suche nach Methoden der Bemessung der Bedingungen einer thermalen Umgebung, die mit subjectiven Tolernanzmasstäben übereinstimmen. Zwei Behaglichkeitswahrnehmungen, nämlich Wärme and Frische, werden separat behandelt, und es werden Empfehlungen vorgeschlagen bezüglich der Werte von umgebungsbedingter Parameter, die mit Wahrscheinlichkeit die grösstmöglichste Behaglichkeit im grössten Anteil einer Felduntersuchung hervorrufen

Die Versuche unterstreichen die Bedeutung einer bedeutenden Vielfältigkeit in der Luftbewegung sowie einer richtig gewählten Feuchtigkeit als weniger offensichtliche Faktoren in thermaler Behaglichkeit. Wandtemperaturen, die niedriger sind als die Lufttemperatur eines Raumes sind als häufige Quelle einer drückenden Atmosphäre festgestellt worden. Unbehaglichkeit wird auch empfunden, wenn die Lufttemperatur in der Ebene des Kopfes diejenige des Fussbodens um 5°F übersteigt.

Messungen der Hauttemperatur von 2500 Fabriksarbeitern deuten darauf hin, dass—obwohl die Hauttemperatur enge mit der Wärmeempfindung einer individuellen Person verbunden ist—dieser Faktor zu unbeständig ist, um als Wärmeindex in einer grossen Bevölkerung benützt zu werden.

REFERENCES

AITKEN, J., 1884, Thermometer screens. *Proc. Roy. Soc., Edin.*, **12**, 661; 1887, Addition to thermometer screens. *Ibid.*, **14**, 428.

ARBUTHNOT, J., 1733, *An essay concerning the effects of air on human bodies.* (London: Tonson and Draper).

BARKER, A. H., 1926, Radiant heating. *Proc. Instn. Heat. Vent. Engrs, Lond.*, **25**, 141.

BEDFORD, T., 1923, Kata-thermometric comparisons of methods of heating and ventilation; heating. *Spec. Rep. Ser., Med. Res. Coun., Lond.*, No. 73, 90; 1936, The warmth factor in comfort at work. *Rep. Industr. Hlth. Res. Bd., Lond.*, No. 76; 1946, Environmental warmth and its measurement. *Med. Res. Coun., Lond., War Memo.*, No. 17; 1954, Comfort in relation to warmth and ventilation—the results of recent studies. *J. Instn. Heat. Vent. Engrs., Lond.*, **22**, 85.

BEDFORD, T., and ANGUS, T. C., 1923, Kata-thermometric comparisons of methods of heating and ventilation: ventilation. *Spec. Rep. Ser., Med. Res. Coun., Lond.*, No. 73, 93.

BEDFORD, T., and WARNER, C. G., 1933. The influence of radiant heat and air movement on the cooling of the kata-thermometer. *J. Hyg., Camb.*, **33**, 330; 1934, The globe thermometer in studies of heating and ventilation. *Ibid.*, **34**, 458; 1939, Subjective impressions of freshness in relation to environmental conditions. *Ibid.*, **39**, 498.

BERNAN, W., 1845, *On the history and art of warming and ventilating rooms and buildings, etc.* (London: G. Bell).

BUILDING RESEARCH BOARD, 1932, *Report for the year* 1931 (London: H.M.S.O.).

CHRENKO, F. A., 1953, Heated ceilings and comfort. *J. Instn. Heat. Vent. Engrs., Lond.*, **20**, 375; **21**, 145; 1955, The assessment of subjective reactions in heating and ventilation research. *Ibid.*, **23**, 281; 1957, The effects of the temperatures of the floor surface and of the air on thermal sensations and the skin temperature of the feet. *Brit. J. Industr. Med.*, **14**, 13.

DRYSDALE, J. W., 1950, Climate and the design of dwellings. *Commonwealth Exptl. Bldg. Stn., Dupl. Document*, No. 32.

DUFTON, A. F., 1929, The eupatheostat. *Phil. Mag.*, 7th ser., **4**, 888; 1932, The equivalent temperature of a room and its measurement. *Bldg. Res. Tech. Pap.*, No. 13; 1936, The equivalent temperature of a warmed room. *J. Instn. Heat. Vent. Engrs., Lond.*, **4**, 227.

ELLIS, F. P., 1953, Thermal comfort in warm and humid atmospheres: observations on groups and individuals in Singapore. *J. Hyg., Camb.*, **51**, 386.

FLÜGGE, C., 1905, Ueber Luftverunreinigung, Wärmestauung und Lüftung in geschlossen Räumen. *Zeitschr. f. Hyg.*, **49**, 363.

GENERAL BOARD OF HEALTH, 1857, Report by the Commissioners appointed to inquire into the warming and ventilation of dwellings.

GLICKMAN, N., INOUYE, T., KEETON, R. W., and FAHNESTOCK, M. K., 1950, Physiological examination of the effective temperature index. *Trans. Amer. Soc. Heat. Vent. Engrs.*, **56**, 51.

HAMBLY, W. D. and BEDFORD, T., 1921, Preliminary notes on atmospheric conditions in boot and shoe factories. *Rep. Industr. Fatigue Res. Bd., Lond.*, No. 11.

HEALTH OF MUNITION WORKERS COMMITTEE, 1916, Ventilation and lighting of munition factories and workshops. *Memo.* No. 9, Cd. 8215.

HEBERDEN, W., 1826, An account of the heat of July, 1825; together with some remarks upon sensible cold. *Phil. Trans. Roy. Soc., Lond.*, Pt. II, 69.

HERMANS, J. T. F., 1883, Ueber die vermeintliche Ausathmung organischer Substanzen durch den Menschen. *Arch. f. Hyg.*, **1**, 1.

HERRINGTON, L. P., and LORENZI, R. J., 1949, Effect of panel location on skin and clothing surface temperatures. *Heat, Pip. Air Condit.*, **21**, 107.

HILL, L., 1914, Report on ventilation and the effect of open air and wind on the respiratory metabolism. *Rep. Loc. Govt. Bd. Publ. Hlth., N.S.*, No. 100.

HILL, L., FLACK, M., MCINTOSH, J., ROWLANDS, R. A., and WALKER, H. B., 1913, The influence of the atmosphere on our health and comfort in confined and crowded places. *Smithsonian Miscell. Coll.*, **60**, No. 23, Publn. No. 2170.

HILL, L., GRIFFITH, O. W., and FLACK, M., 1916, The measurement of the rate of heat-loss at body temperature by convection, radiation and evaporation. *Phil. Trans. Roy Soc., Lond., B.*, **207**, 183.

HOUGHTEN, F. C., and YAGLOGLOU, C. P., 1923, Determining lines of equal comfort., *Trans. Amer. Soc. Heat. Vent. Engrs.*, **29**, 163; 1924, Cooling effect on human beings produced by various air velocities. *Ibid.*, **30**, 193.

HOUSE OF COMMONS (VENTILATION), 1931, Cmd. 3871 (London: H.M.S.O.).

INTER-DEPARTMENTAL COMMITTEE ON TERMINOLOGY, ETC., in Heating and Ventilation Research, 1932, Summary of recommendations. *Building Res. Bd.* (1932), Appendix 1.

League of Nations Health Organization, 1937, The hygiene of housing: Report by the Housing Commission. *Bull. Hlth. Organization of the League of Nations*, **6**, Extract No. 12.

Leblanc, F., 1842, Recherches sur la composition de l'air confiné. *Ann. de chimie et de physique*, **5**, 223.

Leopold, C. S., 1947, Conditions for comfort. *Trans. Amer. Soc. Heat. Vent. Engrs.*, **53**, 295.

Leslie, J., 1804, *An experimental inquiry into the nature and propagation of heat.* (London: J. Mawman).

Morin, J., 1863, *Etudes sur la ventilation.* (Paris: Librairie de L. Hachette et Cie).

Munro, A. F., and Chrenko, F. A., 1949, The effect of radiation from the surroundings on subjective impressions of freshness. *J. Hyg., Camb.*, **47**, 288.

Pettenkofer, M., 1862–3, Ueber die Respiration. *Ann. d. Chem. u. Pharm., Supplement*, **2**, 1.

Reid, D. B., 1844, *Illustrations of the theory and practice of ventilation.* (London: Longman, Brown, Green & Longmans).

Rubner, M., 1897, Experimentelle Untersuchungen über die modernen Bekleidungssysteme. II. Hygienische Gesichtspunkte zur Beurteilung einer Kleidung. *Arch. f. Hyg.*, **31**, 142.

Smith, F. E., 1955, Indices of heat stress. *Med. Res. Coun., Lond., Memo*, No. 29.

Tredgold, T., 1824, *Principles of warming and ventilating public buildings, dwelling-houses, etc.* (London: Josiah Taylor).

Turner, D., 1955, Radiative and convective stimuli of threshold intensity. *J. Hyg., Camb.*, **53**, 32.

Underwood, C. R., and Ward, E. J., 1961, The radiation area of the erect human body with respect to the sun. *Proc. 3rd Internat. Congress on Photobiology.* (In the press).

Vernon, H. M., 1930, The measurement of radiant heat in relation to human comfort. *J. Physiol.*, **70**, 15P; 1932, The measurement of radiant heat in relation to human comfort. *J. Industr. Hyg.*, **14**, 95.

Vernon, H. M., and Bedford, T., 1922, Two investigations in potters' shops. *Rep. Industr. Fatigue Res. Bd., Lond.*, No. 18.

Vernon, H. M., Bedford, T., and Warner, C. G., 1926 a, A physiological study of the ventilation and heating of certain factories. *Rep. Industr. Fatigue Res. Bd., Lond*, No. 35; 1926 b, The influence of cooling power and of variability of air currents on sensations of air movement. *Sp. Rep. Ser. Med. Res. Coun., Lond.*, No. 100, Pt. III; 1930, A study of heating and ventilation in schools. *Rep. Industr. Hlth. Res. Bd., Lond.*, No. 58.

Vernon, H. M., and Manley, J. J., 1926, The measurement of variations in the velocity and temperature of air currents. *Sp. Rep. Ser. Med. Res. Coun., Lond.*, No. 100, Pt. I.

Vernon, H. M., Vernon, M. D., and Lorrain-Smith, I., 1928, A physiological investigation of the radiant heating in various buildings. *Rep. Industr. Fatigue Res. Bd., Lond.*, No. 46.

Vernon, H. M., and Warner, C. G., 1932, The influence of the humidity of the air on capacity for work at high temperatures. *J. Hyg., Camb.*, **32**, 431.

Ward, E. F., 1930, The measurement of skin temperature in its relation to the sensation of comfort. *Amer. J. Hyg.*, **12**, 130.

Winslow, C.-E. A., Herrington, L. P., and Gagge, A. P., 1937 a, Relations between atmospheric conditions, physiological reactions and sensations of pleasantness. *Amer. J. Hyg.*, **26**, 103; 1937 b, Physiological reactions of the human body to varying environmental temperatures. *Amer. J. Physiol.*, **120**, 1.

Yagloglou, C. P., and Miller, W. E., 1925, Effective temperature with clothing. *Trans. Amer. Soc. Heat. Vent. Engrs.*, **31**, 89.

Yaglou, C. P., 1926, The thermal index of atmospheric conditions and its application to sedentary and to industrial life. *J. Industr. Hyg.*, **8**, 5; 1927, Temperature, humidity, and air movement in industries: the effective temperature index. *Ibid.*, **9**, 297.

Yaglou, C. P., and Drinker, P., 1928, The summer comfort zone: climate and clothing. *J. Industr. Hyg.*, **10**, 350.

MAINTAINING THE LEVEL OF VIGILANCE BY MEANS OF KNOWLEDGE OF RESULTS ABOUT A SECONDARY VIGILANCE TASK*

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An experiment is reported in which performance of a central vigilance task was maintained at a high level by giving knowledge of results concerning performance on a peripheral vigilance task which was undertaken concurrently. Knowledge of results consisted of displaying response time to the onset of a signal in the secondary task, response time connoting the degree of alertness with respect to the central task. There appear to be implications for the design of an alertness indicator.

§ 1. Introduction

In two earlier papers (Baker 1959 a, b) it was shown that an expectancy theory of vigilance can account for the maintenance of vigilant performance when knowledge of results is given. In another paper (Baker 1960) it was shown how a high level of vigilance could be maintained by combining knowledge of results with artificial signals. The present paper is concerned with the addition to a central, or main task of a secondary, or peripheral vigilance task, knowledge of results being supplied for performance on the secondary task only. The form of the knowledge of results was in this case designed to be purely motivational.

§ 2. Apparatus

For the central task the display was a one-inch square of milk glass viewed from a distance of about 18 in. by the subject seated in a booth. Signals, small spots of light 2 mm in diameter and lasting 6/10 sec, appeared in any of the four corners of the display. Signal brightness was well above threshold for foveally fixated signals. The subject's task was simply to press a button when a signal was detected.

Features of the apparatus with respect to the secondary task were as follows. Ambient illumination from an indirect source in the ceiling of the booth provided 0·01 f.c. at the display and a 1000 cycle tone provided a continuous low hum of 67 dB. The experimenter could increase the illumination or loudness by arbitrarily chosen increments. In the case of the illumination the increment was 0·12 f.c., while in the case of the sound it was 0·5 dB. The illumination and tone features provided the secondary vigilance display, the subject's task being to press a second response button when a secondary 'signal' was detected, i.e. when a change in illumination or loudness became apparent. In addition there was a small curtained digital readout display above the central display. Under the two experimental conditions this display indicated the subject's response time to the secondary signals.

Subjects, 90 paid women, were selected at random from a pool of 110 which is used in experiments conducted at the Defence Research Medical Laboratories. All were the wives of Royal Canadian Air Force personnel on a neighbouring air base. They were arbitrarily divided into five groups of 18, one group being assigned to each of five conditions. Subjects were employed singly.

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Instruction to Subjects

As the instructions were of great importance, and because they help clarify the procedure, they are reproduced below for each of the five groups.

Control Group I

> " This is an experiment to find out how watchful people can be in a rather boring task. In the small square in front of you a tiny signal light will appear from time to time and you are to press this button as soon as you see it. The signal light will appear in any one of the 4 corners of the square. (Demonstration of a signal light in each corner.) You'll have to be watchful all the time because you don't know when a signal light will appear, or which corner it will appear in. Sometimes a long time will elapse between signal lights : at other times they may seem to be fairly frequent. Just press the button whenever you see one. Altogether you will be in here an hour and a half. Any questions ? "

The ambient sound and illumination were both employed at their lowest level but the subjects' attention was not drawn to them.

Experimental Group I (Illumination)

This group received the same instructions as Control Group I, to which the following was added.

> " Now there is a second job for you to do. You will notice that there is some light in this room from above, though not very much. After a while the light will begin to get brighter quite suddenly. As soon as you know it is getting brighter I want you to press this OTHER button. When you press this OTHER button the room light will go back to dim. You can tell whether you are being watchful for signals or not from the time it takes you to notice the light getting brighter. All you have to do is to raise this little curtain and you'll see a number. If the number says 4, for example, it means it took you 4 seconds before realizing that the light was getting brighter. If it says 27, then it was 27 sec before you realized that it was getting brighter. If your time score is 10 or less than 10 then you are fairly wide awake and you are probably seeing most of the small lights. If your score is more than 10 then you are not being very watchful : you may be falling asleep and you are probably missing a lot of signal lights. Then you must make an effort to wake up so as not to miss any more signal lights. The room light might get brighter several times though this will happen much less often than the signal lights will. Any questions ? "

Experimental Group II (Tone)

This group received identical instructions to Experimental Group I (Illumination) with the exception that the words ' noise ', ' low ' and ' louder ' were substituted for ' light ', ' dim ' and ' brighter '.

Control Group II (No Knowledge of Results)

This group also received the same instructions as Control Group I, to which the following was added.

> " Now there is a second job for you to do in this room. You will notice that there is some noise in this room though not very much. After a while

the noise will begin to get louder quite suddenly. As soon as you know it is getting louder I want you to press this OTHER button. When you press this OTHER button the noise will again become low. The noise will get louder several times though this will happen much less often than the signal lights will. Any questions? "

It will be apparent that this condition was like that for Experimental Group II except that knowledge of results (response time) was not displayed on the digital readout display, nor was it referred to.

Control Group III (*Probability Instructions*)

This group also received similar instructions to Control Group II, with two exceptions. The first sentence with respect to the secondary task was, " Depending on how things go there may be a second job for you." The other exception was the addition at the end of the instructions of, " If the noise never seems to get louder don't worry about it. As I said above, it depends on how things go whether you get noise signals as well as the tiny light signals."

The experiment ran for 1½ hours. In the central task the intervals between subjects were the same as those used originally by Mackworth (1950, see also Baker 1959 a), the 12 inter-signal intervals in each half-hour ranging from 45 to 645 sec. Each subject was exposed to a different random order of these inter-signal intervals each half-hour. Five secondary signals were inserted during periods when there was sufficient time between central signals to ensure that the secondary signal would be detected before another central signal occurred : they consequently came at different times for each subject. None were inserted in the first half-hour on the task, the first always occurring between 30 and 32 min. from the start of the experiment. Two more occurred in the second half-hour, and the last two in the third half-hour. No secondary signals were closer together than six minutes.

§ 3. RESULTS

The percentage of missed detections for each half-hour were subjected to an arc sine transformation and an analysis of variance performed, as given in Table 1. From this table it is apparent that there was a significant difference

Table 1. Analysis of Variance of Transformed Numbers of Missed Detections

Source of Variance	*Degrees of freedom*	*Mean Square*	*F*
C1 Light vs. Noise	1	0·4269	1·9
C2 Control 2 vs. Control 3	1	0·0498	0·2
C3 Control 1 vs. Controls 2 & 3	1	0·0940	0·4
C4 Experimental vs. Controls	1	5·7781	26·8*
Between Conditions Total	4	1·5872	7·3*
Error 1 (Between Ss within Groups)	85	0·2153	
T (Between Half-Hours)	2	0·0058	0·1
TC	8	0·0541	0·9
Error 2 (Remainder)	170	0·562	
Total	269		

* Significant at 0·01 level of confidence.

between conditions only, the difference being almost completely accounted for by the two experimental versus the three control conditions. There were no significant differences among control or among experimental conditions, and no significant performance changes with time in any of the five conditions.

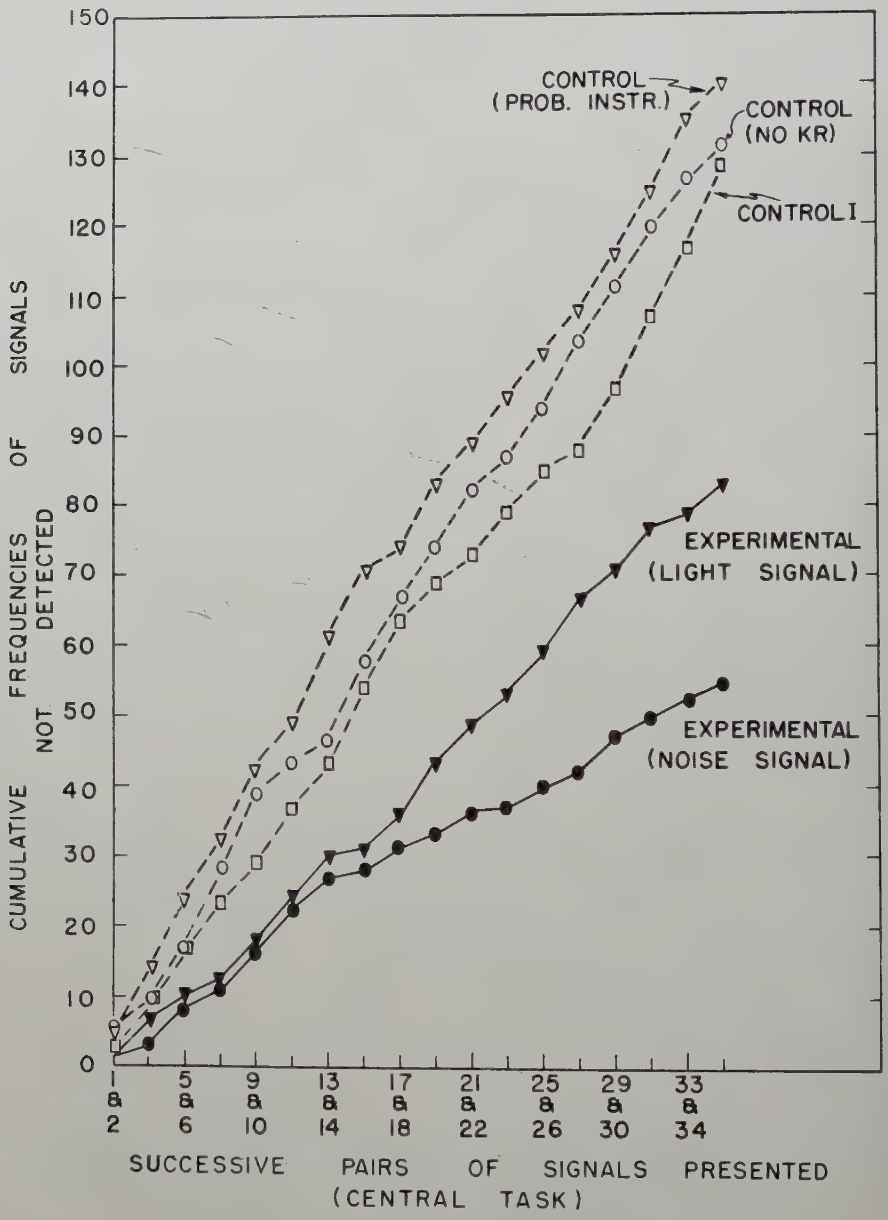

Figure 1. Showing cumulative frequencies of signals missed out of 36 presented in 90 minutes, for each of the five experimental conditions.

When plotting the data an attempt was made to avoid the conventional and generally unsatisfactory technique of plotting mean performance for each half-hour (smaller temporal intervals on the abscissa usually being avoided because when inter-signal intervals are randomly different for each subject, smaller plotting intervals represent different frequencies of signal presentation). Instead, a cumulative frequency graph was constructed, as shown in Fig. 1. The abscissa values are successive pairs of signal presentations, pairs being chosen simply because 18 steps were convenient for plotting purposes. While still not completely satisfactory (different subjects would have been presented with, say, signals 7 and 8 at different times) such a plot gives a general indication of performance over the whole period of the task.

From Fig. 1 it is apparent that the three control groups performed throughout the task in remarkably similar fashion : a conventional plot shows a decrement trend which, however, is not significant (Table 1). Performance of the two experimental groups was superior to that of the control groups even early in the task and this superiority was maintained throughout the task—indeed, the group which had the tone as a secondary signal showed an apparent though non-significant increment in performance after completion of the first half-hour, i.e., after the first peripheral signal was detected. As noted in Table 1, the divergence of the experimental groups from each other is not significant.

With respect to the secondary task, response times in both experimental groups showed some improvement over the five signals. This improvement was not significant in the case of the tone signals but it was, at the ·01 level of confidence, for the illumination signals. Only 9·5 per cent of the secondary signals were responded to in 10 sec or less by either experimental group.

§ 4. Discussion and Conclusion

The five conditions were employed in the order given above for the following reasons. When the first control and the two experimental conditions had been completed it was shown statistically that the experimental conditions resulted in performance superior to that of the control group, even during the first half-hour when no peripheral signals were presented. Consequently two questions arose. The first was whether the superior performance of the experimental groups was due to the knowledge of results supplied, or simply to the fact that there were peripheral signals in addition to those of the central task. To supply an answer Control Group II was employed. The second question was specifically concerned with performance during the first half-hour. It appeared that the superiority of the experimental groups was a consequence of instructions, i.e. subjects in the two experimental groups had been instructed that peripheral signals were definitely going to occur, whereas they were not mentioned to the control group. To test this hypothesis Control Group III was employed, subjects in this group being instructed in how to respond to peripheral signals, but at the same time being left in doubt concerning their possible occurrence. (This procedure appeared not unwarranted in view of the relatively homogeneous pool of subjects, and in the manner of their assignment to conditions. The clear-cut nature of the subsequent results confirmed its adequacy.)

An interesting point concerns the possibility that, with less variation between subjects, the tone condition results might have been significantly superior to those of the illumination condition. A possible explanation for such a superiority would be that as in the illumination condition the secondary and the central tones shared the same sensory modality, subjects sometimes missed central signals because they were momentarily searching for secondary signals. If true, then the implication for the use of a secondary task in practical situations is that it be attended to by a sensory modality other than that employed in the central task.

With respect to the form of motivation employed by the experimental groups it must be pointed out that whereas the display of response times was instrumental in maintaining the initial level of vigilance on the central task it is still not certain whether the display of response times was itself the responsible factor, or that the great majority of responses were such that failing alertness was indicated, or that any connotation concerning alertness is needed, or, possibly, because of the implication that the experimenter knew the subject's response times. This latter possibility of implied evaluation by other persons as a motivating factor in vigilance tasks has generally been overlooked : in the one pertinent experiment known to the writer (Fraser 1953) the presence of an experimenter in a room in which subjects performed a vigilance task resulted in performance superior to that when the experimenter was absent.

Our general conclusion is that the knowledge that signals on a secondary vigilance task will definitely occur, though at unknown frequencies, is a factor which, at least early in a task, results in superior performance on a central vigilance task. When the secondary signals do begin to occur, the high level of performance on the central task is maintained by knowledge of results on the secondary task which connotes the degree of alertness with respect to the central task. The implications for an alertness indicator appear obvious.

On rapporte une expérience dans laquelle la performance à une tâche de vigilance centrale a été maintenue à un niveau élevé en faisant connaître les résultats obtenus à une tâche périphérique entreprise concurremment. Cette connaissance des résultats consistait à exposer le temps de réaction à la presentation d'un signal dans la tâche périphérique, ce temps de réaction impliquant le dégré de prestesse concernant la tâche centrale. Certaines implications pour la construction d'un indicateur de vigilance sont discutées.

Ein Experiment wird rapportiert in welchem die Leistung einer centralen Wachtsamkeitsaufgabe auf einem hohen Niveau beibelhalten war durch Kundmachung der Ergebnisse betreffend die Leistung einer peripherischen Wachtsamkeitsaufgabe die gleichlaufend unternommen war. Die Kundgebung der Ergebnisse besteht in Amzeigen der Reaktionsperiode auf den Beginn eines Signals in der peripherischen Aufgabe, wo die Reaktionsperiode zugleich den Wachtsamkeitsgrad mit Beziehung auf die centrale Aufgabe bedeutet. Es scheint hier interessante Andeutungen für den Entwurf eines Wachtsamkeitindikators vorhanden zu sein.

References

Baker, C. H., 1959 a, Three minor studies of vigilance. *Defence Research Board of Canada, DRML* Report No. 234–2 ; 1959 b, Towards a theory of vigilance. *Cdn. J. Psychol.*, **13**, 35–42 ; 1960, Maintaining the level of vigilance by means of artificial signals. *J. appl. Psychol.*, **44**, 336–338.

Fraser, D. C., 1953, The relation of an environmental variable to performance in a prolonged visual task. *Quart. J. exp. Psychol.*, **5**, 31–32.

Mackworth, N. H., 1950, Researches on the measurement of human performance. *Medical Research Council* Special Report No. 268. (London : H.M.S.O.).

ESTIMATING AVERAGES

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An investigation is described of ability to estimate averages of several values of a variable presented either symbolically or graphically. Symbolic information was presented to subjects on small white cards on which were typed between 10 and 20 two-digit numbers. Graphical information was presented as 10 to 20 points on inch, ruled tenths, graph paper. In most cases described, subjects were allowed ten seconds to examine the information for judgement. With symbolic information they were allowed unlimited time after this in which to form a judgement, but with graphical information the examination time included the setting of a cursor line at a position across the graph corresponding to the judged average value. The information presented varied not only in amount but also in scatter of the values about their mean.

The results show that for both symbolic and graphical information, the error of judgement increases with increasing amount and scatter of material presented. The effects of increasing amounts of information are much more marked with high scatter than with low scatter material. Differences between subjects were negligible amongst students but were pronounced among a group of chemical process operators. Scatter was much the most important variable affecting averaging accuracy and some interesting results were obtained when the material presented contained one item markedly different in value from its fellows.

The results are discussed and further experiments are suggested to increase an understanding of the mechanisms of statistical judgements.

§ 1. Introduction

An investigation of the work of process operators suggested that one component of the skill they use might be the ability to estimate averages from the varying indications provided by plant instruments. In order to deal with departures from the desired condition of plant operation an operator must build up, usually by experience, a mental pattern of correct indications which he compares with current plant indications. By assessing the differences between these two patterns, one purely mental and the other actual, he can decide what corrective action to take. In practice, most plant indications are varying continuously due to several factors, so that the operator must form an average estimate of some sort for each indication from which to derive his mental pattern.

Process operators never report consciously adding up successive values and dividing the total to obtain an average. Hence the process must be unconscious or performed in a manner very different from that of the statistician. Since no published evidence seemed to be available on this problem some simple experiments were performed to determine what factors influence the averaging process.

§ 2. Experiment I

Symbolic material used with student subjects

In this experiment subjects were required to estimate the averages of sets of numbers printed on cards. All the numbers used were two digit groups with one or two exceptions where either one or three digits were used. The information for each judgement was arranged in columns of five figures on square white cards of 3 in. side. The values of the numbers were scattered approximately normally about their means which were all whole numbers in the range 20 to 80. Scatter was varied in different sets of cards in such a way that the standard deviations were kept fairly constant at two levels designated *low scatter* (from about 2·0 with 10 items to about 3·0 with 20) and *high scatter* (from about 8·0 with 10 items to about 19·0 with 20).

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The subjects were two groups of eight women students (median age 19 years) from the Fine Arts Department of Reading University. One group judged low scatter material and the other high. Each group made ten judgements of ten items and ten of twenty with each of two lengths of exposure, 5 and 10 sec, i.e. 40 judgements in all.

Each subject had the nature of the task explained to her and was shown examples of the cards. She was told to assess the single value which would best represent the series presented or to estimate 'the average value' suggested by the series. The term 'average' was used in the conversational sense without any definition or qualification. Only if the subject, as happened occasionally, asked if the 'mathematical average' was wanted was she told 'yes'. Quite often subjects made the comment "Oh, you mean you want me to add the numbers and then divide by the number presented?" On the reply "Yes, but you won't have time to add, you have to estimate instead" the invariable response was "Oh well, you can't expect me to do that, it'll be a waste of time". (One of the pleasures of the experiment from the experimenters' point of view was to see the sheepish grins of pride and surprise on the subjects' faces when, at the conclusion of their judgements, they were shown how well they had performed).

After this preliminary instruction and answering of questions the subject proceeded to make a judgement for each of the cards used in the experiment. She was allowed unlimited time to make her judgement—only the time of presentation was controlled. The session generally lasted about twenty minutes to half an hour. No information about the success, or otherwise, of judgements was given until the end of the session.

2.1 *Results*

The mean errors (taking sign into account) are set out in Table 1. All the deviations from correctness, except one (for 20 items with high scatter observed for 10 sec), are very small, and the general overall accuracy of the judgements must be regarded as remarkably high.

Table 1. Mean errors made by students judging averages of symbolic material

Time for which material was presented (sec)	5		10	
Number of items	20	20	10	20
Mean errors taking sign into account:				
Low scatter material	−0·01	−0·21	−0·04	−0·10
High scatter material	+0·05	−0·09	+0·09	+2·29
Mean errors regardless of sign:				
Low scatter material	0·62	1·01	0·44	0·92
High scatter material	2·57	7·28	1·88	6·01

Each value is the mean of 80 observations: 10 judgements by each of 8 subjects

The mean errors (regardless of sign) are also shown in Table 1, from which it can be seen that error rose substantially with number of items and fell a little with increased exposure time. Analyses of variance showed the former to have been highly significant for both high and low scatter material only.

The errors with high scatter material were substantially greater than those with low, and all four differences were shown to be significant by t tests. These differences could, strictly speaking, have been due to the subjects who judged low scatter material having been superior to those who judged high, but in view of the fact that both groups were drawn from the same population, and that subject differences within the two groups were insignificant, it seems safe to conclude that the differences of errors between high and low scatter material were in fact due to the different amounts of scatter.

§ 3. EXPERIMENT II

Symbolic material used with industrial process operators

This experiment was performed at a large organic chemical factory on 18 process operators (median age 44 years) who volunteered to act as subjects. A balanced design of two factors, number of items and amount of scatter, at each of three levels was employed. Every subject made 10 judgements under each of the nine conditions. Knowledge of results was withheld until after the experimental session was completed.

The three different numbers of items were ten, fifteen or twenty and the scatter conditions were low, high and the low scatter condition with one value included which differed markedly from the others. This last will be referred to as the *single deviant condition.*

Exposure time was held constant at 10 sec. The choice of 10 rather than 5 sec was to reduce any effects due to purely mechanical differences in eye movement patterns between subjects. Very few subjects seemed able to add even ten numbers in their heads in the 10 sec allowed, but in case they were tempted to try, they were told not to use this method.

The procedure was otherwise similar to that of Experiment I.

3.1 *Results*

The mean errors (taking sign into account) were again small except that for 20 items of high scatter. They are set out in Table 2. Also shown in Table 2 are the mean errors (regardless of sign). The differences between errors of this latter type with low and high scatter material are similar to those of Experiment I confirming the conclusion that the former results were a function of the material and not of the different groups of subjects. As before, the increase of error with number of items is much greater for high than for low scatter material.

Table 3 compares the errors (regardless of sign) for process operators and students in the conditions for which a comparison can be made. The students are in all cases better, although they are significantly so only for the low scatter conditions. The ratio differences become less as the difficulty of the conditions increases.

Unlike the students, the process operators showed significant individual differences in their ability to average. To examine these differences in more detail, operators were ranked in order of increasing total error (regardless of sign) under the condition of low scatter 10-item presentation. This was the condition in which individual difference was least significant. The ranking was then divided into three groups of six operators each, a best group (low error), an average group and a worst group (high error). The performances of the three groups were then evaluated for the remaining judgement conditions.

The results, set out in Table 4, show that the three groups, with one small exception, retain their relative positions throughout all the conditions. The worst group is, however, much more affected by the combination of high scatter and greater numbers of items than the average or best groups.

Table 2. Mean errors made by process operators judging averages of symbolic material

Number of items	10	15	20
Mean errors taking sign into account :			
Low scatter material	−0·21	−0·32	−0·28
High scatter material	+0·01	+1·02	+3·71
Single deviant material	−0·63	−0·26	−0·39
Mean errors regardless of sign :			
Low scatter material	1·09	1·66	1·59
High scatter material	2·94	6·42	8·00
Single deviant material	2·55	2·55	2·64

Each value is the mean of 180 observations : 10 with each of 18 subjects.

Table 3. Differences of mean error (regardless of sign) between students and process operators

	Low scatter		High scatter	
	10 items	20 items	10 items	20 items
Process operators' mean *minus* students' mean	0·66	0·66	1·06	1·99
Ratio of process operators' to students' means	2·48	1·73	1·56	1·33

Table 4. Errors (regardless of sign) of process operators divided into 'best', 'average' and 'worst' groups

	Low scatter			High scatter			Single deviant		
Number of items	10	15	20	10	15	20	10	15	20
Group									
Best	0·55	1·30	1·27	2·33	4·40	5·41	1·65	1·98	2·25
Average	1·05	1·40	1·33	3·50	5·87	7·09	2·28	2·78	3·10
Worst	1·68	2·26	2·17	3·00	9·02	11·50	3·71	2·88	2·56

Each value is the mean of 60 observations : 10 judgements by each of 6 subjects.

Errors (regardless of sign) with the single deviant series were, for each number of items, significantly higher than for the corresponding low scatter series. Error seems to have been virtually unaffected by amount of material in the single deviant series—the 'rogue' seems to have masked the effect of amount of material. Estimates were biased in the direction of deviations of the 'rogue' significantly more frequently than would be expected by chance : operators gave too much weight to the 'rogue' when making their estimates. This effect appeared to be more marked in the average group of subjects than in the best and worst.

The question whether the magnitude of judgement error is proportional to the magnitude of the deviation of the 'rogue' was examined for each of the three groups separately. Correlations were calculated between deviant magnitude and error magnitude on ten and twenty item lists. Since there were ten cards for each list length, there were ten pairs of observations for each correlation. The magnitude of a deviation was expressed as the difference between the deviant value and the average of the remaining items on card, divided by the average of the remaining values. This produced deviations of either positive or negative sign depending on whether the deviant was less than or more than the average. Table 5 shows the results obtained. All correlation coefficients are positive but only those of the average group are significant. This suggests that only in the case of the average group of subjects is there a fairly direct and proportional response to the deviant. The tendency is present among the members of the best and the worst groups but not to a significant degree. Hence one might conclude that there is a general tendency to respond in ‘ sympathy ’ with a ‘ rogue ’ and in proportion to its degree of deviation, but that this tendency is marked only in a small proportion of subjects.

Table 5. Correlations between deviant magnitude and error magnitude for three groups of subjects at each of two conditions of information amount

Condition	r & p	Subject Group		
		Best	Average	Worst
10 item	r	+0·421	+0·670	+0·564
	p	>0·1 N.S.	<0·05>0·02	<0·05>0·5 N.S.
20 item	r	+0·512	+0·903	+0·408
	p	>0·1 N.S.	<0·001	>0·1 N.S.

§ 4. GRAPHICAL MATERIAL USED WITH STUDENT SUBJECTS

For graphical presentation, the same numbers used for symbolic presentation were translated into y-axis distances and separated at equal intervals of $\frac{1}{2}$ in. along the x-axis of a graph plotted on 1 in. graph paper ruled every 1/10 in. Units of 1/10 in. corresponded to the units of the numbers used for symbolic presentation. A small dot with a circle round it denoted each individual value.

When a graph was to be judged it was placed on a small horizontal platform, attached to which by means of sprocket wheels and chains was a strip of celluloid with a hair-line inked along its central major axis. By rotating one of the two hand wheels provided for the purpose the hair line could be made to travel at right angles to its length over the graph. The subject had to position the hair line on the graph at a position corresponding to his estimate of the mean of the plotted points. In effect the hair line was a movable x-axis. Because of this arrangement, the ten seconds allowed for studying the graph also included the time taken to reach a decision, whereas with the symbolic presentation, the subject could ponder as long as he liked before reporting his decision. With graphical presentation there is therefore an element of pacing which was not present with symbolic presentation.

4.1. *Results with low and high scatter*

In the first part of the experiment, eight men students (median age 20 yrs.) made three judgements of graphical means at each of two scatter conditions (low and high) and two amounts of information (ten and twenty points). The orientation of the cursor, and hence of the graphs, was systematically changed between the four cardinal directions so that in different presentations the positive direction of the y-axis was in the 12 o’clock, 3 o’clock, 6 o’clock, and 9 o’clock directions.

The results, shown in Table 6, were similar to those obtained under symbolic averaging conditions in spite of what might be thought of as a fundamental difference between the two tasks. In symbolic averaging, one must assume that the process is completely abstract in nature, while graphical averaging would appear to be a visual perceptual judgement. The graphical judgement situation becomes similar in some ways to the judgements of balance made in experiments on visual aesthetics (Pierce 1894, Puffer 1903). Three subjects specifically expressed their judgements as attempts to achieve visual balance when asked for introspections after the experimental session. Two others reported that judgement was based on the ‘ visual feel ’ of the total display—i.e. of the graph points and cursor hair line. An analysis of variance showed only the scatter effect to be significant : there were no significant differences of error (regardless of sign) for different numbers of items or between subjects.

Table 6. Mean errors made by students judging averages of graphical material of low and high scatter

	Low scatter		High scatter	
Number of items	10	20	10	20
Mean errors taking sign into account	−0·13	−0·31	+0·001	+0·97
Mean errors regardless of sign	0·37	0·59	0·79	2·21

Each value is the mean of 24 observations : 3 judgements by each of 8 subjects.

4.2. *Results with the single deviant series*

In the second part of the experiment a further eight men students estimated the averages of graphically presented material for ten and twenty points which included a ‘ rogue ’ deviant. There was one slight difference between the ‘ rogue ’ values in this experiment and Experiment II : in the symbolic series the ‘ rogue ’ was sometimes high and sometimes low ; in the graphical material it was always high.

The average error rose, as might be expected, as compared with low scatter series, but as in Experiment II there was no rise of error with an increase from 10 to 20 items.

The bias produced by the ‘ rogue ’ was negative, that is the ‘ rogue ’ was under-weighted. Thus the effects of a ‘ rogue ’ value were opposite for graphical and for symbolic material. The possibility was examined that with the graphical material the subjects were ignoring the ‘ rogue ’. This was done by testing whether the mean error scores when error is measured from the graph mean with the ‘ rogue ’ value excluded differed from zero. The difference was significant for both 10 point graphs ($t = 6{\cdot}629$, $p < 0{\cdot}001$) and for 20 point graphs ($t = 3{\cdot}416$, $p < 0{\cdot}02 > 0{\cdot}01$), so it seems obvious that subjects were responding to the ‘ rogue ’, and were genuinely under-estimating its contribution to the graph mean.

For neither part of this experiment were the effects attributable to varying cursor orientation consistent.

Table. 7. Mean errors made by students judging averages of single deviant graphical material

Number of items	10	20
Mean error taking sign into account :	−0·76	−0·004
Mean error regardless of sign :	0·90	0·95

Each value is the mean of 24 observations : 3 judgements by each of 8 subjects.

4.3. *Prediction from graphical material*

After making each average judgement the cursor was removed and subjects were asked to predict where the next point would be on the assumption that the ten (or twenty) points plotted had arrived successively after equal intervals of time. The subject was to suppose that he was waiting for the eleventh (or twenty-first) point to appear and had to predict where it was most likely to be. Unlimited time was allowed for this and the subject, when he had made his decision, placed a small piece of celluloid with a dot and ring engraved on it in the position corresponding to his prediction.

The predictions for the first part of the experiment (low and high scatter material) were subjected to an analysis of variance to discover factors affecting the predictions. The major contributions to prediction of variance were the amount of material, its scatter and the interaction between these two variables. Subject differences were insignificant. This result is interesting because it provides an example of a complex judgement situation in which different people tended to give similar answers to a problem for which there is no 'correct' or absolute answer at all. Taking both parts of the experiment together, for sixteen of the eighteen graphs the 95 per cent fiducial limits to the mean predictions enclosed the actual graph mean. Hence subjects stayed fairly close to the graph mean in their predictions. In other words they assumed that the 'system' represented by the plotted points would not behave unexpectedly.

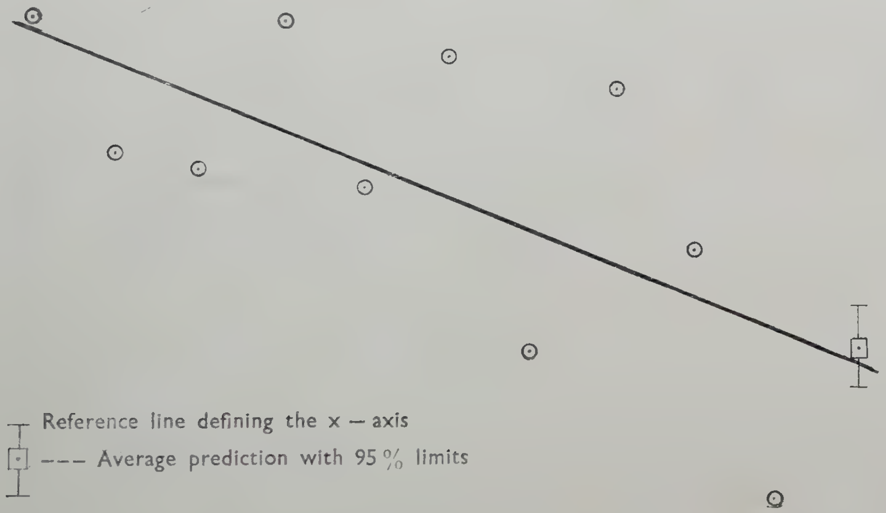

Figure 1. High scatter 10 item graph. Mean prediction of 8 subjects. Also shown is best fitting straight line of graph points.

A further interesting point is illustrated in Fig. 1; namely that subjects responded sensitively to any discernible trend in graphical material. Since all the values plotted on each graph were obtained from random normal deviate tables the 'trend' visible in Fig. 1 was fortuitous and was in fact the clearest example of trend in any of the eighteen graphs used. However the best fitting straight line of these graph points passes almost exactly through the mean prediction. After the experiment was completed it appeared from a visual examination of the graphs and their predictions that trend detection as a preliminary to prediction of the 'future' was usually based on one of two sets of data. The example illustrated is one of long-term prediction—all the points plotted serve to indicate the trend. Examples of short term trend predictions occurred when the points were scattered more or less obviously at random as shown in Fig. 2. In these cases the last three or four points (i.e. those immediately preceding the prediction value) were used to define a trend and prediction was based on this. Both types of trend abstractions were in fact specifically mentioned by some subjects ; and although only one was able to report that ' I always found a pattern from which to make my prediction ', only one reported that prediction was ' sheer guess work '.

There were large time differences in prediction, some people taking several minutes and others making a decision after a brief appraisal. Unfortunately times were not recorded as it was felt desirable not to focus the subjects' attention on the time they took. Several subjects ' acted out ' their predictions by moving the prediction point about and examining the visual result at each of several settings before making their decision.

§ 5. Discussion

5.1. *Graphical versus symbolic presentation*

The fact that the variability of judgement is considerably reduced with graphical as compared with symbolic presentation, may be taken to mean that the direct visual estimation of ' balance ' was easier than the more complex abstraction required with symbolic presentation. Precise comparison is, however, difficult because with graphical presentation subjects obtained visual knowledge of the satisfactoriness of their result by seeing the cursor line running across the graph. With symbolic presentation no objective indication of the relation between judgement and data was given to subjects. It seems possible that this difference explains the rapidity with which graphical judgements were made compared with the much longer ' deliberation time ' usually taken for symbolic judgements.

The influence of amount of information on judgement is much reduced with graphical presentation. This again may be due in part to the visual feedback inherent in the graphical presentation, but seems likely to be due also to the greater ease with which a visual ' impression ' can be formed from the collection of graph points. This is presumably the same type of phenomenon as that often utilized by experimenters when plotting correlation diagrams in order to ' see what the data looks like '. Helson (1948) has shown that people respond to sensory stimuli in a manner which suggests that response to one stimulus is a function of the average of all preceding similar sensory stimuli. He points out that all sensory adaptation can be regarded as a form of weighted averaging inherent in the operation of sensory processes.

5.2. *Effects of number of items*

It is interesting to compare the present results with those reported in a series of papers by Irwin and his colleagues (1956 a, b, 1957). In their experiments subjects were presented with cards, each with a single number printed on it either positive or negative and nearly zero in value. Subjects had to estimate whether the mean value of the whole pack of similar cards was less or greater than zero. Cards were presented until the subject felt confident enough in his judgement to reach a decision and report it. The

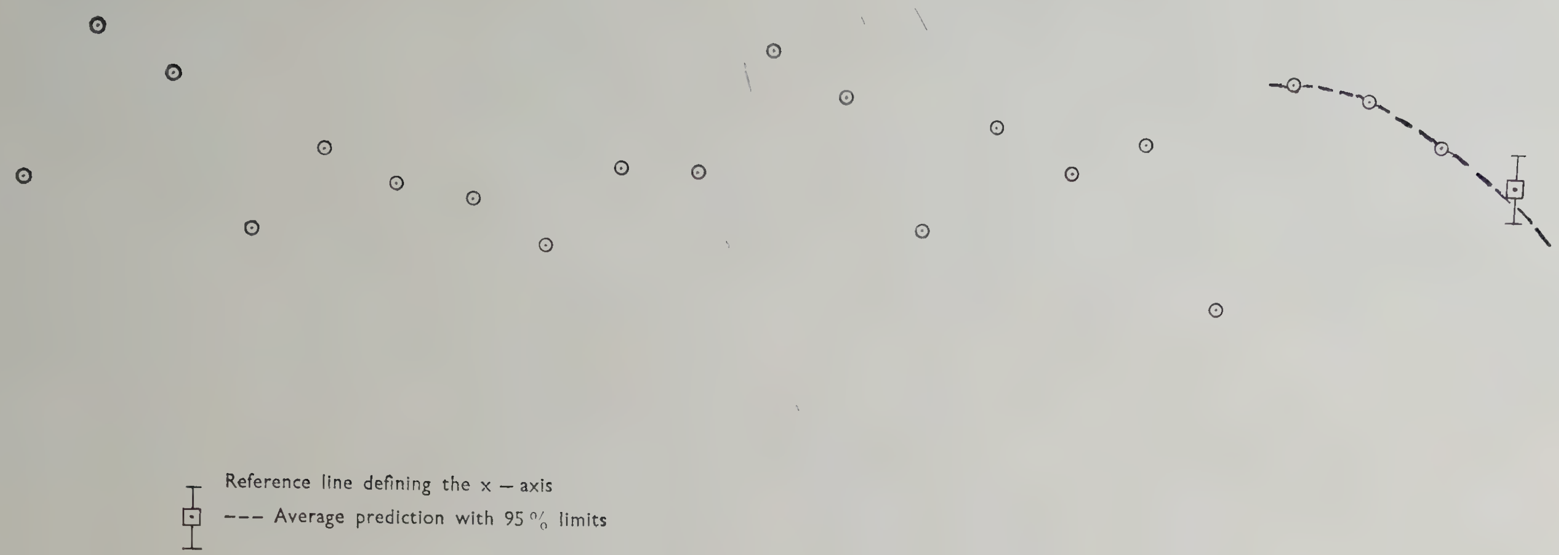

Figure 2. Low scatter 20 item graph: mean prediction of 8 subjects.

mean and standard deviations of the numbers in a pack were varied. The presentation of information thus corresponds to an externally imposed succession of symbolic material, but the judgement is rather different from those required of subjects in the present experiments. Irwin and his colleagues found that the number of cards required to be seen was greater when the absolute value of the mean was near zero and when the standard deviation of the numbers seen was higher. Of particular interest is the fact that when subjects rated their degree of confidence in their judgement on each occasion, the rating increased with increase in number of cards, and varied inversely with the standard deviation of the numbers presented. There is agreement therefore between Irwin's and the present results in finding that increased scatter leads to greater uncertainty in judgements, revealed in the present experiments by the greater variability of judgement with high scatter. There is however a discrepancy between the two sets of results with respect to the effect of increased amounts of information. Irwin's subjects showed greater confidence in their judgements with increase in number of items seen, whereas in the present experiments accuracy of judgement tended to fall as the number of items rose. A reason for this might be that in Irwin's case the subjects were given a hypothesis to test or evaluate so that every additional item of information confirmed or denied the given hypothesis. In the present experiments subjects had in effect to find or create a hypothesis which unified the mass of unrelated information. Under these conditions, as the amount of data increases the more difficult it becomes to find a ' suitable ' value which covers all the data.

5.3. *Individual differences*

It has already been noted that for symbolic averaging that differences between students were practically non-existent but between process operators they were markedly significant, and students seemed to be rather better at averaging than process operators. If it is assumed that formal education plays little part in developing the ability to average quantitative symbolic material, then, either averaging ability is a highly specific ability or else it is a function of general intellectual capacity. If it were a highly specific ability one would expect to find larger differences between students. So it is more reasonable to assume that it is related to general intellectual ability, since students are selected on this basis, whereas the sample of process operators probably included people covering a much wider range. Unfortunately measures of intelligence were not obtained from the process operators. It is hoped that the relationship between intelligence and averaging ability can be examined in a future experiment.

The individual differences in response to ' rogue ' values shown by the process operators were, as we have seen, chiefly attributable to the ' average group of operators. Men either more or less capable seemed to be less affected by the ' rogue '. A possible explanation lies in the fact that the ' rogue ' seems to stand out from the other values and this tends to attract undue attention. It may be that the best subjects are able to overcome this tendency and thereby maintain a more even weighting of the items of information. At the opposite extreme the worst subjects may not structure the data sufficiently to see the ' rogue ' as standing out from the others.

5.4. *Trend analysis of graphical information*

The consensus of agreement between subjects in predicting a ‘ future ’ position in terms of the average shown by the data already presented is similar to some experimental results reported by Bartlett (1958) using a type of verbal extrapolation task which permitted a large variety of possible solutions. His subjects in fact utilized a very small proportion of the possible range, and as the information about a required solution increased, subjects tended to choose increasingly similar extrapolations.

When considering the observation that people detect consistent trends with considerable accuracy, it should be noted that the average prediction for the group of subjects agreed closely with the best-fitting *straight line* prediction. This latter is the simplest relationship that could be used to describe the plotted points : other more complex relations might fit the data better. It is interesting to find that the easiest mathematical relationship appears also to be the simplest perceptual relationship abstracted from the data by subjects. This is plausible if it is assumed that subjects were in fact mentally assessing the average with reference to rotated co-ordinates and extrapolating from this ‘ tilted ’ average. Since people apparently estimate averages remarkably accurately, they presumably will achieve similar results when the axis along which the average lies is slightly tilted with respect to the x and y axis originally used to define the positions of the plotted points. The directness of the perceptual judgement is in marked contrast to the laborious arithmetical operations necessitated by the restriction to the co-ordinate system in terms of which the data are described. The beauty of the perceptual system seems to be that it derives its frame of reference or its ‘ co-ordinates ’ from the data themselves thereby eliminating the intervening calculations necessary to translate from arbitrary co-ordinates into those of data.

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APPENDIX

Root Mean Square Errors

		Low scatter			High scatter			Single deviant		
	Number of items :	10	15	20	10	15	20	10	15	20
eriment I, udent subjects.	Symbolic material, 5 sec exposure	0·78	—	1·00	3·53	—	8·97	—	—	—
	10 sec exposure	0·73	—	1·36	2·50	—	7·61	—	—	—
eriment II, rocess operators.	Symbolic material, 10 sec exposure	2·02	2·54	2·15	6·26	8·98	10·63	4·42	3·43	3·95
eriment III, udent subjects.	Graphical material, 10 sec exposure	0·50	—	0·95	0·93	—	2·96	1·15	—	1·13

L'article décrit une recherche portant sur la capacité d'estimer la moyenne de plusieurs valeurs d'une variable, présentées soit sous forme symbolique, soit sous forme de graphique. L'information symbolique était présentée aux sujets à l'aide de petites cartes blanches sur lesquelles étaient imprimés entre 10 et 20 nombres de 2 chiffres. L'information graphique était présentée sous forme de 10 à 20 points, sur papier graphique à l'échelle du pouce subdivisé en dixièmes. Dans la plupart des cas décrits, les sujets disposaient de 10 secondes pour examiner l'information. Avec l'information symbolique, ils disposaient ensuite d'un temps illimité pour porter un jugement, mais avec l'information graphique, le temps d'examen comprenait aussi la mise en place d'un curseur, transversalement au graphique, à une position correspondant à la moyenne estimée. L'information présentée variait non seulement en quantité, mais aussi par la dispersion des valeurs autour de leur moyenne.

Les résultats montrent que tant pour l'information symbolique que pour l'information graphique, l'erreur de jugement augmente avec la quantité et la dispersion des données présentées. Les effets de l'accroissement de la quantité des données sont beaucoup plus marqués avec une forte dispersion qu'avec une faible dispersion des nombres. Les différences interindividuelles étaient négligeables parmi des étudiants, mais prononcées parmi un groupe d'opérateurs de l'industrie chimique. La dispersion est, de loin, la plus importante variable affectant la sûreté de l'estimation.

Quelques résultats intéressants furent obtenus quand le matériel présenté contenait une donnée fortement différente des données voisines par sa valeur.

Les résultats sont discutés et d'autres expériences sont suggérées pour améliorer la compréhension des mécanismes des jugements statistiques.

Es wurde die Fähigkeit untersucht, den Durchschnittswert verschiedener Werte einer Variablen zu schätzen, die entweder sinnbildlich oder graphisch dargeboten wurden. Sinnbildliche Informationen wurden den Versuchspersonen auf kleinen weissen Karten geboten, auf die 10–20 zweistellige Zahlen gedruckt waren. Graphische Information erfolgte durch graphische Darstellung von 10–20 Zahlen als Punkte in einem Koordinaten-System. In den meisten Fällen standen den Versuchspersonen 10 sec zur Verfügung, um die Information zu prüfen. Danach durften sie bei sinnbildlicher Information beliebige Zeit zur Urteilsbildung verwenden. Bei der graphischen Information musste dagegen in den 10 sec Prüfzeit ein durchsichtiges Lineal mit einer Haarlinie so verschoben werden, dass sie die dargebotenen Punkte mittelte. Die gebotene Information variierte nicht nur in ihrer Quantität, sondern auch in ihrer Streuung um den Mittelwert.

Die Ergebnisse zeigen, dass sowohl bei sinnbildlicher wie bei graphischer Information der Beurteilungsfehler mit der Menge und Streuung der Information zunimmt. Die Wirkungen grösserer Informations-Menge sind bei grosser Streuung des Materials sehr viel höher als bei kleiner Streuung. Individuelle Unterschiede waren unter Studenten zu vernachlässigen, dagegen auffallend in einer Gruppe von Chemie-Facharbeitern. Streuung war die bei weitem wichtigste Variable, welche die Genauigkeit der Mittelwertsbildung beeinflusste. Einige interessante Ergebnisse wurden erhalten, wenn das gebotene Material eine von den übrigen deutlich verschiedene Grösse enthielt.

Die Resultate wurden diskutiert und weitere Experimente vorgeschlagen, um das Verständnis des Mechanismus statistischer Urteile zu verbessern.

REFERENCES

BARTLETT, SIR F. C., 1958, *Thinking—An Experimental and Social Study*) 1st Ed.) (London: George Allan & Unwin Ltd.).

HELSON, H., 1948, Adaptation level as a basis for quantitative theory of frames of reference. *Psychol. Rev.*, **55**, 297–313.

IRWIN, F. W., SMITH, W. A. S., and MAYFIELD, J. F., 1956, Tests of two theories of decision in an expanded judgement situation. *J. exp. Psychol.*, **51**, 261–266.

IRWIN, F. W., and SMITH, W. A. S., 1956, Further tests of theories of decision in an expanded judgement situation. *J. exp. Psychol.*, **52**, 345–350 ; 1957, Value, cost and information as determiners of decision. *Ibid.*, **54**, 229–233.

PIERCE, E., 1894, Aesthetics of simple forms. *Psychol. Rev.*, **1**, 483–495.

PUFFER, E. D., 1903, Studies in symmetry. *Psychol. Monog.*, **4**, No. 17, 467–539.

CHANGES IN PERFORMANCE AT A SERIAL-REACTION TASK UNDER CONDITIONS OF ADVANCE AND DELAY OF INFORMATION

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An experiment is reported which compared, in a continuous serial choice-reaction task, the effects of giving the display signals at different points either before or after the responding limb was in a position to take appropriate action. The results indicated that substantial elements in the timing of serial, sensori-motor performance are the times required to deal with sensory data arising from limb movements and possibly, although to a lesser extent, times taken to overcome inertia in the apparatus or in a moving limb. The presence of these elements provided an explanation of the fact that advance information did not speed up performance as much as would be expected if the whole of the performance time was available for dealing with the signals in the display.

§ 1. Introduction

The present experiment was designed to follow out, within a single context, two lines of previous work. First, that of Leonard (1953) who found in a serial choice-reaction task that if the signals for action were given a little before the point in time at which a choice of action had to be made, performance was quicker, although the time saved was less than the time by which the signals were advanced. The present experiment studies the effect of advance information in more detail with a view to finding why this was so.

The second line is represented by the work of Singleton (1953, 1954), Wehrkamp and Smith (1952) and others who have divided the total time taken to perform a continuous sensori-motor task into components, separating actual *movement times* from times when no movement is taking place. They have found that the latter, apparently because they reflect times taken to perceive the display and initiate (as opposed to execute) action, show more effects of practice, voluntary change of speed, age of subject, etc.

The display of Singleton's apparatus consisted of four lights, which appeared in random order, positioned at the ends of the arms of a cross (Fig. 1). The control was a lever which could move along channels in four directions from a centre point. Each light was responded to by moving the control lever in a horizontal plane in a direction corresponding to the direction in which the light signal appeared in the vertical display. Thus if the light at the top of the cross came on the Subject moved the control lever away from him, if the light at the bottom came on the Subject moved the lever towards him, if the light came on at the left the Subject moved the lever to the left, and so on. Moving the lever to the end of the correct channel put out the light which was on, and returning the lever to the centre brought on the next light. Singleton was thus able to separate rigorously the ‘ centre ’ organizing times, which were essentially reaction times, from the movement times of the lever in the channels, and he found that the former were more subject to variation with age and fatigue than the latter.

It was not certain, however, how far the centre times in Singleton's experiments were strictly reaction times to the signals and how far they included times required for attention to the inevitable kinaesthetic and other signals accompanying movement which would have occurred on arrival back at the centre after traversing a channel: these, if they did not overlap with the reaction times to the next signal, would have lengthened the centre times. In Singleton's case such signals might have arisen not only from the sudden deceleration of movement on reaching the centre, but from the fact that at this moment the apparatus produced a loud click. Certain aspects of a theory put forward by Welford (1952) on psychological ' refractoriness ' interpreting results by Vince (1948, 1949) and others suggest that attention to kinaesthetic and other signals may set limits upon the speed of performance of this type of task, and clear evidence that they can do so is given by the same author (Welford 1959), although as Davis (1956) has shown, they may in certain circumstances cease to do so with long practice.

The present experiment was designed as a further study of the time taken by these processes involving attention to kinaesthetic and other cues and also as an attempt at a more precise quantitative study of the effects of advance information in a sensori-motor skill.

§ 2. Method and Procedure

Singleton's apparatus was used with a timer included in the display unit circuit in order *either* to delay the onset of the next signal after the return to the centre on completion of the previous movement, *or* to advance the onset of each signal so that it came before the return to the centre of the previous movement. The amount of the delay varied from 0 sec to 0·5 sec and the amount of the advance was varied from 0 sec to 0·25 sec. The advance signal was timed to occur at a given time after reaching the end point (E in Fig. 1). The precise upper limit of the amount of advance thus varied from subject to subject depending on the mean duration of each subject's time spent at E and in making the movement back to the centre.

The Subject's performances were recorded to the nearest hundredth of a second on an electronic digital machine (N. Welford 1952). For each correct response under normal conditions without delay or advance three time measures were recorded: (i) *centre time*, i.e. the time between the appearance of the stimulus and the initiation of the response; (ii) *outward movement time*, i.e. the time to move the lever from the centre to the end of the channel; and (iii) *return time*, i.e. the time spent between arriving at the outward end point and arriving back at the centre. In terms of Fig. 1 these correspond to the time spent at C, the time spent in moving from C to E, and the time elapsing after arrival at E and before arrival back at C. Under the condition when advance information was given, the *total reaction time* to a stimulus as measured from the onset of the signal to the beginning of the responding movement would be the sum of the time spent at C plus the time between the onset of the stimulus and the subject's arrival back at C. Under the delay condition the total reaction time to a stimulus would be the time spent at C minus the time by which the signal was delayed. Under the normal condition the total reaction time would be equal to the time spent at C.

The procedure evolved as the experiment progressed and as points of interest and importance emerged from the preliminary stages. The final procedure adopted for each experimental session was as follows: four trials under the normal condition followed by from six to nine trials under advance

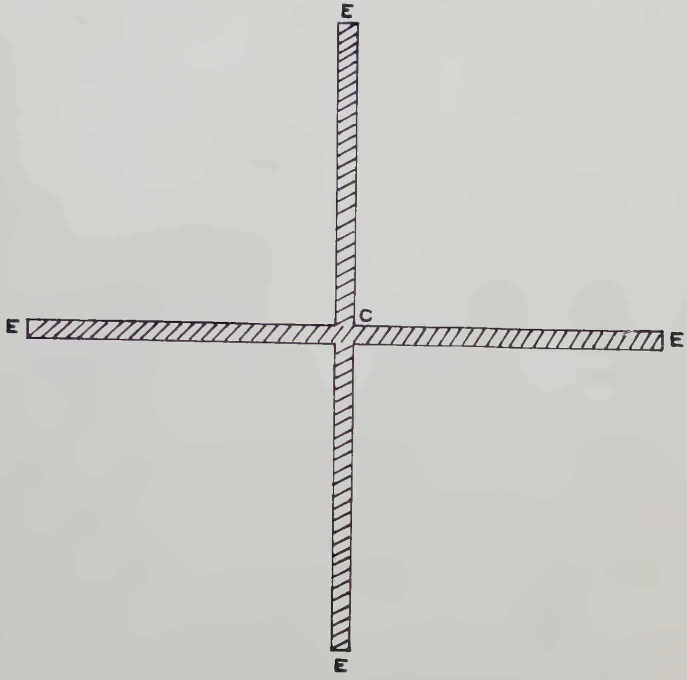

Figure 1. The shaded area represents the possible paths of movements in the Subject's responses to the display.

conditions followed by two further trials under the normal condition and finishing with one trial under the delay condition. Of the three subjects, A and B followed this plan fully, while Subject C had the final delay trials omitted, and in his later sessions also the further normal trials. In all, Subject A had 135 trials, Subject B 107 trials and Subject C 114 trials. Each trial consisted of responding to 64 light signals.

After each trial the subject was told the total time taken for the trial and the number of ' large ' errors made. A ' large ' error was scored when the subject went to the outer end point of an incorrect channel.

§ 3. Results

The principal results were that:

(i) The *total reaction time* under conditions of very slight advance was significantly greater than the total reaction time under normal conditions. For all subjects this difference was significant at the 1 per cent level of confidence as shown by a *t* test.

(ii) The total reaction time when the next signal was delayed by 0·1 sec was significantly less than the total reaction time under normal conditions. For the two subjects tested in this condition the difference was significant at the 2 per cent level of confidence as shown by a *t* test.

Table 1 gives the centre time, total reaction time and return time for the three subjects at the last session of their training. These three measures

Table 1. The centre time, total reaction time and return time for the Subjects at their final session of training

		Experimental Condition													
		Normal at Start	Advance in seconds											Normal at End	Delay
			0·03	0·05	0·06	0·08	0·09	0·10	0·14	0·16					0·10
Subject A 135 trials 8640 responses	Centre time	0·20	0·19	0·17	0·16	0·14	0·12	0·11	0·10	0·11				0·19	0·25
	Total reaction time	0·20	0·22	0·22	0·22	0·22	0·21	0·21	0·24	0·27				0·19	0·15
	Return time	0·15	0·15	0·15	0·15	0·15	0·15	0·14	0·16	0·16				0·15	0·17
			0·01	0·07	0·10	0·12	0·15	0·19							0·10
Subject B 107 trials 6848 responses	Centre time	0·24	0·27	0·21	0·19	0·16	0·15	0·14						0·23	0·30
	Total reaction time	0·24	0·28	0·27	0·29	0·28	0·30	0·33						0·23	0·20
	Return time	0·19	0·19	0·21	0·20	0·20	0·19	0·21						0·19	0·19
			0·01	0·02	0·04	0·07	0·09	0·11	0·13	0·14	0·17	0·19	0·21		
Subject C 114 trials 7296 responses	Centre time	0·20	0·22	0·21	0·19	0·18	0·18	0·16	0·15	0·11	0·11	0·12	0·11		
	Total reaction time	0·20	0·23	0·23	0·22	0·24	0·26	0·27	0·27	0·25	0·29	0·31	0·32		
	Return time		0·21	0·20	0·20	0·21	0·21	0·21	0·21	0·20	0·21	0·21	0·21		

Table 2. The component times for Subject C's performance at three stages of training

		Experimental Condition												
		Normal at Start	Advance in seconds											Normal at End
			0·12	0·13	0·13	0·14	0·16	0·16	0·19	0·19	0·25	0·26		
After 17 trials	Centre time	0·29	0·25	0·22	0·23	0·22	0·21	0·22	0·19	0·19	0·17	0·14		0·28
	Total reaction time	0·29	0·37	0·34	0·36	0·36	0·37	0·39	0·38	0·38	0·43	0·40		0·28
	Return time	0·32	0·28	0·27	0·31	0·26	0·26	0·24	0·23	0·25	0·27	0·26		0·25
			0·03	0·03	0·06	0·06	0·09	0·11	0·12	0·14	0·16	0·18	0·20	
After 47 trials	Centre time	0·20	0·24	0·24	0·25	0·22	0·22	0·20	0·17	0·17	0·18	0·14	0·11	
	Total reaction time	0·20	0·26	0·27	0·31	0·29	0·31	0·31	0·29	0·31	0·34	0·32	0·31	
	Return time	0·23	0·33	0·21	0·20	0·22	0·21	0·21	0·20	0·20	0·20	0·20	0·20	
			0·01	0·02	0·04	0·07	0·09	0·11	0·13	0·14	0·17	0·19	0·21	
After 114 trials	Centre time	0·20	0·22	0·21	0·18	0·18	0·18	0·16	0·15	0·11	0·11	0·12	0·11	
	Total reaction time	0·20	0·23	0·23	0·22	0·24	0·26	0·27	0·23	0·25	0·29	0·31	0·32	
	Return time		0·21	0·20	0·20	0·21	0·21	0·21	0·21	0·20	0·21	0·21	0·21	

are shown in seconds under the various experimental conditions used and the amount of advance and delay given in each case is indicated.

Table 2 presents the data for Subject C at three separate stages of training roughly corresponding to the beginning, middle and end of his familiarity with the task.

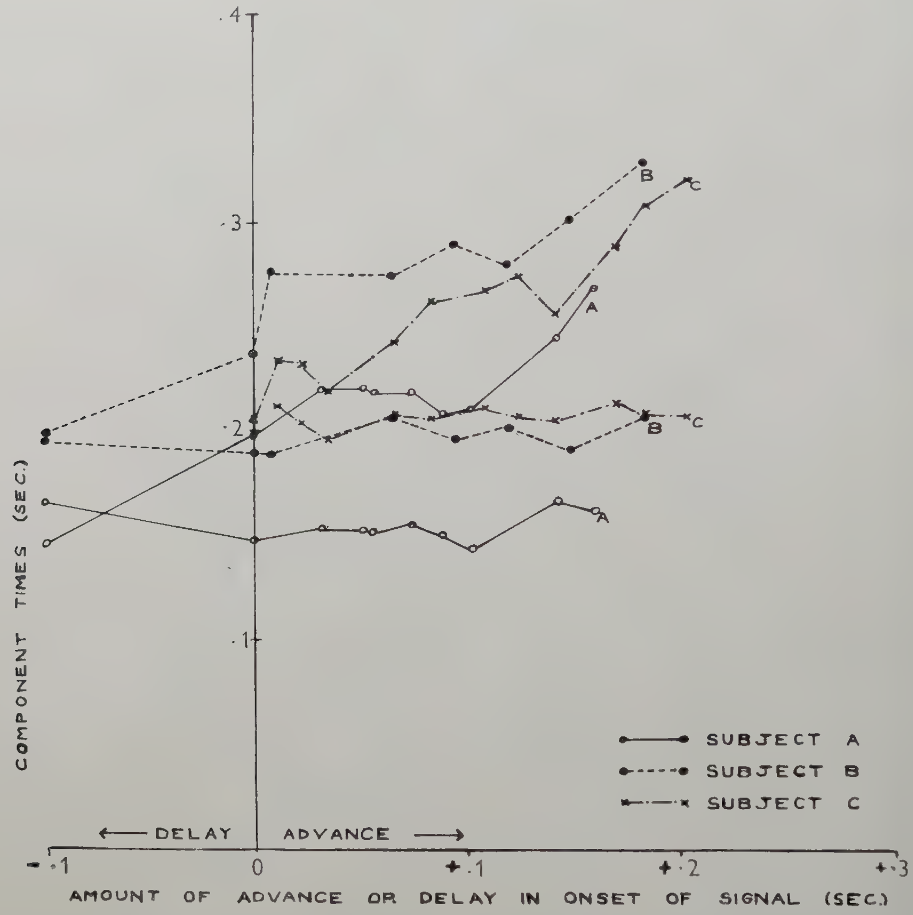

Figure 2. Changes in total reaction times with changes in advance and delay information times. For each Subject the upper line represents the total reaction time and the lower line the sum of return movement and turn round time.

Figure 2 shows graphically the change in total reaction times with changes in advance and delay information times for the three subjects. Each point on the graph represents the mean for one trial of 64 responses.

Figure 3 shows graphically the change in *centre time* with increasing amounts of advance for the three subjects. Each point on the graph represents the mean for one trial of 64 responses.

§ 4. Discussion

Reaction times under advance, normal and delay conditions

When the next signal is given in advance of the completion of the response to the previous signal we should expect that if the advance information could be completely used the resultant total reaction time to the signal should remain

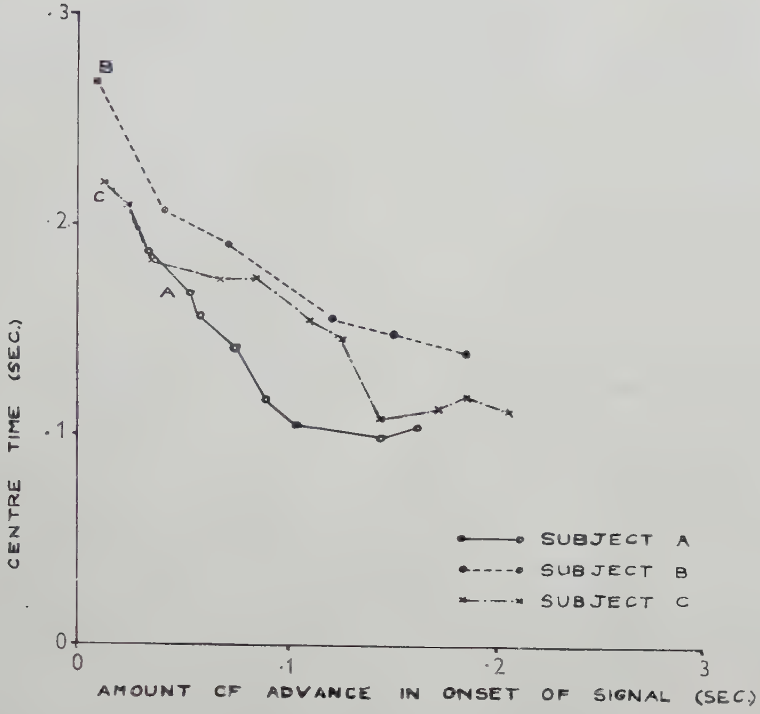

Figure 3. Changes in centre times with increasing amounts of advance information for three subjects.

steady until the amount of advance exceeds the minimum centre time and that then the reaction time should start to rise. This centre time would always be greater than zero owing to the fact that there would inevitably be a short ' turn-round ' time required on grounds of the sheer mechanics of limb movement, and possibly because of other factors discussed below.

The experimental results (Fig. 2) are not, however, as expected in that there is a substantial increase in total reaction time with the smallest advances and that over substantial ranges of further advances total reaction time remains relatively steady. It would therefore appear that some extra component is added to the values of total reaction time under advance conditions. It is not possible from the experimental data to give a definite indication of what this extra component is, but we may reasonably suppose that it is connected with the fact that in the advance condition the subject has *both* to deal with the signal *and also* with some sensory data about getting back to the centre. With the normal condition these two events occur at the same instant and the latter may therefore be redundant. If so, we should expect on general information-theory grounds that time would be saved.

We should not expect that when the two events are simultaneous time would be saved in *all* cases since simultaneous events are not necessarily treated as such. We might, however, expect that if a delay is introduced between the subject's returning to the centre and the onset of the next signal, the data indicating that the centre point had been reached could be dealt with during the delay and therefore the reaction time to the signal could be reduced. Total reaction times under the delay condition did show a reduction, as would be expected on this view (Fig. 2).

The present results permit an estimate to be made of the *maximum* time required for dealing with the sensory data indicating that the centre has been reached. This will be the difference between the reaction time with a very small advance and the reaction time with a delay of duration sufficient to produce maximum saving of total reaction time. The times, according to Table 1, would be about 0·04 sec for Subject A and about 0·06 sec for Subject B.

Minimum centre time

The time spent dealing with sensory data indicating that the centre had been reached needs to be distinguished from the minimum possible centre time. This latter could, perhaps, be measured directly by taking the centre time when the lever was moved round and round the four channels in turn as quickly as possible without any signals. The minimum time may be due in part to the time required to deal with sense data, and in part to mechanical limitations either in the apparatus or in moving the limbs to make responding movements. Such mechanical delays could not account for the whole of the discrepancy between advance and delay conditions. They might account for the difference between normal and delay conditions but could not be the cause of the rise of reaction time when a small advance is given. They could probably overlap with the reaction to the signals but not with the attention to data signifying that the centre had been reached since they are dependent upon the latter.

An estimate of the mechanical delay involved can be obtained by considering the *minimum* time spent at the centre under conditions such that we should expect the centre time to be very short (Fig. 3). As the amount of advance increases so the centre time falls with the total reaction time remaining fairly steady until a limit is reached (Fig. 3). Beyond this limit the centre time remains steady and the total reaction time rises (Figs. 2 and 3). The difference between this minimum centre time and the maximum estimate of time taken to observe reaching the centre (see paragraph 2 above) should give a *minimum* estimate of the mechanical delay time. For Subject A this will be 0·027 sec and for Subject B 0·065 sec.

There is however another possible cause of there being a minimum centre time, which would lead to another estimate of minimum mechanical delay time, and it is this. We should perhaps expect that time would be required to observe reaching the outer end-point and also to initiate a return movement in the same manner as time is required at the centre. This is not directly measured in the present experiment, but could be inferred by subtracting the outward movement time from the return time (both of which measures we have) on the not unreasonable assumption that the movement is of equal duration in both directions (i.e. C to E and E to C). Applying this to Subject B's results we have an outward movement time of 0·05 sec, a return time of 0·19 sec, and therefore 0·14 sec of this available for dealing with the next signal. His minimum reaction time with a delay was 0·20 sec and therefore the minimum centre time should be 0·06 sec. In fact, as measured under conditions of maximum advance, it was 0·14 sec—an excess of 0·08 sec. Deducting from this the 0·06 sec estimated as the maximum time for dealing with sensory data consequent on reaching the centre, we are left with 0·02 sec as the minimum mechanical component time. This time is small, but it is a minimum and assumes that the mechanical component cannot be overlapped with the times required for dealing with a new signal or with sense data arising from a return to the centre.

The view of the subjects' performance which has been outlined may be summarized as follows:

(*a*) When the onset of the signal is coincident with the return of the control lever to the centre it would appear that the two events, i.e.

   (i) the new signal,

   (ii) the sense data arising from the fact that the centre has been reached, are dealt with concurrently or that one of them becomes redundant. There is no way in this experiment of distinguishing between these two alternatives.

(*b*) When the onset of the signal is delayed until some time after the return of the control lever to the centre and the delay is longer than the time taken to monitor arrival at the centre and bring the lever to rest, the reaction time to the signal is greatly reduced and gives a minimum estimated value of the time taken actually to deal with the new signal.

(*c*) When however the signal is given after the control lever arrives at the outer end-point and before arrival back at the centre, the total reaction time rises due to the fact that the subject has both to deal with the new signal and with the data consequent on arrival back at the centre, and can neither treat the latter as redundant, nor overlap the times required for dealing with them.

This experiment was carried out whilst the author was a member of the Nuffield Unit for Research into Problems of Ageing at the University of Cambridge. The author gratefully acknowledges his indebtedness to Mr. A. T. Welford for guidance and encouragement throughout the work.

L'article rapporte une expérience qui, dans une tâche continue de choix multiple en série, compare les effets d'une présentation de signal lorsque le membre se trouve en diverses positions, en deçà ou au delà de la position optima pour l'exécution de la réponse.

Les résultats ont montré que les éléments essentiels dans l'organisation temporelle d'une performance sensori-motrice en série sont les temps requis pour répondre à des données sensorielles venant de mouvements de membres et peut-être, quoique de manière moindre, les temps nécessaires pour vaincre l'inertie de l'appareil ou du membre en mouvement.

La présence de ces éléments a fourni une explication du fait qu'une information anticipée n'accélère pas la performance autant qu'on pourrait l'espérer si la totalité du temps de performance était disponible pour exploiter les signaux.

Es wird über ein Experiment berichtet, in welchem in einer fortlaufenden Reihe von Wahlreaktions-Aufgaben die Auslösungs signale zu verschiedenen Zeitpunkten, entweder bevor oder nachdem das reagierende Glied sich wieder in Bereitschaftsstellung befand, gegeben wurden.

Die Resultate zeigen, dass wesentliche Faktoren in der Zeitbemessung für fortgesetzte sensomotorische Leistungen die Zeiten sind, welche zur Verarbeitung sensorischer Meldungen über die Stellung der Gliedmassen gebraucht werden. Möglicherweise spielen auch die Zeiten, die zur Ueberwindung der Trägheit des Apparates oder der bewegten Gliedmassen benötigt werden, eine gewisse Rolle.

Die Wirkung dieser Faktoren erklärt die Tatsache, dass Voraus-Informationen die Leistung nicht so viel beschleunigen, wie zu erwarten wäre, wenn die gesamte Leistungszeit für die Verarbeitung der Signale zur Verfügung stände.

References

Davis, R., 1956, The limits of the ‘psychological refractory period’. *Quart. J. exp. Psychol.*, **8,** 24–38.

Leonard, J. A., 1953, Advance information in sensori-motor skills. *Quart. J. exp. Psychol.*, **5,** 141–149.

Singleton, W. T., 1953, Deterioration of performance on a short-term perceptual-motor task. In *Symposium on Fatigue* (ed. W. F. Floyd and A. T. Welford) (London: H. K. Lewis for the Ergonomics Research Society); 1954, The change of movement timing with age. *Brit. J. Psychol.*, **45,** 166–172.

Vince, M. A., 1948, The intermittency of control movements and the psychological refractory period. *Brit. J. Psychol.*, **38,** 149–157 ; 1949, Rapid response sequences and the psychological refractory period. *Brit. J. Psychol.*, **40,** 23–40.

Wehrkamp, R. A., and Smith, K. U., 1952, Dimensional analysis of motion: II. Travel distance effects. *J. appl. Psychol.*, **36,** 201–206.

Welford, A. T., 1952, The ‘psychological refractory period’ and the timing of high-speed performance—a review and a theory. *Brit. J. Psychol.*, **43,** 2–19; 1959, Evidence of a single-channel decision mechanism limiting performance in a serial reaction task. *Quart. J. exp. Psychol.*, **11,** 193–210.

Welford, N. T., 1952, An electronic digital recording machine—the SETAR. *J. sci. Instrum.*, **29,** 1–4.

FURTHER EXPERIMENTS ON HUMAN OPERATORS IN COMPENSATORY TRACKING TASKS

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Three experiments on control sensitivity in compensatory tracking tasks are reported using the same apparatus as that used by North *et al.* (1958). The results of the first experiment confirmed the findings of those previously described by North *et al.* on the influence of changing control sensitivities on the accuracy of performance; this experiment differed from that previously reported in the application of *two* different *targets* composed of the same harmonics with changed phases instead of one. In the second experiment the way was studied in which the varying magnification of display and the varying control sensitivity jointly influenced accuracy. In the third experiment tracking with isometric controls was investigated: in this type of control the error is compensated not by the free movements of the handle, but by the operator's exerting varying forces on the controls with practically no handle movements. Performance with this type of control under these particular experimental conditions was found to be superior to that with isotonic controls.

In all three experiments effects of learning were studied as well as performance when learning appeared to be more or less complete. An interesting case of transfer of skill over a period of a year without intervening practice was found.

§ 1. Introduction

The experiments described below concerned the performance of operators in compensatory tracking tasks, i.e. tasks in which the operator can see only the *difference* between his output and the input he is required to match, and formed a continuation of experiments of this kind discussed in a paper by North *et al.* (1958). The experiments in the first paper had as their aim the study of the effects of changes in *sensitivity of controls* on the performance of operators. The object of the present paper is to discuss the results of further experiments with the same apparatus which were conducted at Boulton Paul Aircraft Limited in the years 1958 and 1959 and consisted of the following series:

Experiment I. This was similar to those described in North *et al.* (1958) with the difference that *two targets* were used instead of only one.

Experiment II. This studied the joint effect of changes in *control sensitivity* and in *display magnification* on the performance of operators.

Experiment III. This examined the effects of changes in *control sensitivity* in the case when the *isotonic controls* (i.e. controls allowing for free movements of the handle) used in previous series were replaced by *isometric* controls constructed in such a way that the errors were compensated by the operator's exerting a varying force on the controls with practically no handle movements.

As in the previous series of experiments results were studied with a view to investigating the effects of changes in *experimental variables* on *performance*, but at the same time the effects of *learning* were also observed.

§ 2. Experiment I

2.1. *Method*

The subjects, six works apprentices here denoted by D1–D6, were required to track one of two compound harmonic targets (CHTI or CHTII), the velocity of which, in inches per second, was given by

$$\text{CHTI:}\quad 0{\cdot}25[\cos(2\pi t/30)+1{\cdot}5\cos(2\pi t/10)+1{\cdot}5\cos(2\pi t/5)]$$
$$\text{CHTII:}\quad 0{\cdot}25[\sin(2\pi t/30)+1{\cdot}5\sin(2\pi t/10)+1{\cdot}5\sin(2\pi t/5)].$$

The target CHTI was that used in the experiments of North *et al.* (1958); the comparison between target velocities is shown in Fig. 1. The targets were compounded of the three harmonics having, for each target, the same amplitudes and frequencies but differing in phase. This was done because if the tracking process can be explained adequately by the model of a linear stochastic difference equation proposed by North (1952), then the tracking gives rise to a systematic mean square error depending on the tracked target and to an independently superimposed stochastic mean square error. It is easy to show that under such assumptions the systematic error for two targets compounded in the above way should be the same, and one of the objects of the experiment was to find whether this would be confirmed by experimental results.

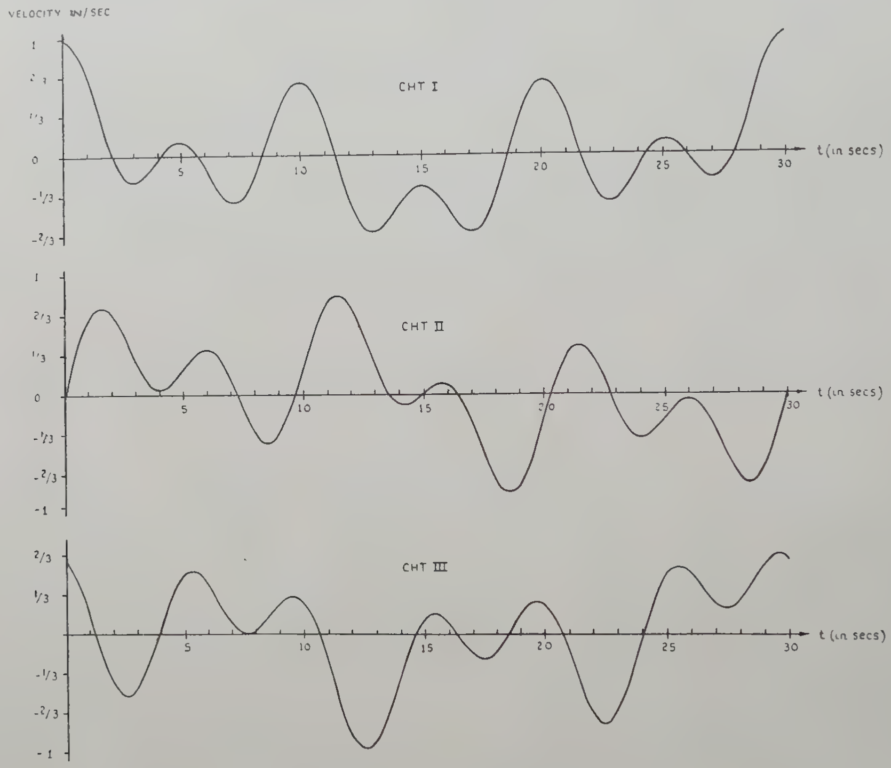

Figure 1. Target velocities.

Velocity control was used throughout. As in the work previously reported the sensitivity range was explored from the lowest sensitivity compatible with the targets to one when ‘ catching ’ the spot was beginning to be uncomfortably difficult. The sensitivities were presented to the operator in steps:

50, 75, 125, 200, 300, 500, 750, 1250, 1750, 2500

measured in thousandths of an inch mils/sec/degree of handle movement.

Each subject made 27 trials, and each trial consisted of one run with each of these sensitivities—i.e. 10 runs in all. To avoid sequential effects the sensitivities were presented in a randomized order as in the earlier experiments. The recorded part of each run lasted 30 secs which is the period of the target, but before recording the results the subject was given 10 secs to adapt himself to the sensitivity and to overcome the effects of starting conditions. The instructions given to the operators were the same as those shown in the Appendix to North *et al.* (1958).

The only difference from the former experiments was that in the present case the targets were changed randomly from one trial to another. This was done in such a way, however, that in the last 10 (and 12) trials each target was presented 5 (and 6) times. By changing the sign of the velocity in CHTI and by reversing the direction of the cam in CHTII it was possible to present each target in two different ways and this was done, but the influence of these changes was not further explored.

2.2. *Learning Results*

The score used in assessing subject's performance in any particular trial was the mean, over all the runs, of his squared error measured in squared mils. The ‘ learning curves ’ showing the decrease of the score in successive trials were very similar in shape to those previously found (North *et al.* 1958, Fig. 3). The changes of scores with learning are given in Table 1 which can be compared with Table 2 in North *et al.* (1958).

Table 1. Changes of scores (in squared mils) with learning

Subject	D1	D2	D3	D4	D5	D6
Initial score	21 805	18 802	39 146	25 524	39 276	30 054
Best score	2 224	3 436	3 366	1 795	3 748	2 343
in trial number	24	22	25	27	27	27
Best score in hundredths of the initial score	10·20	18·28	8·60	7·03	9·54	7·79
Mean score for the last 10 trials	3 072	4 480	4 132	2 191	4 778	2 901
Above score in hundredths of the initial score	14·09	23·83	10·55	8·58	12·17	9·65

The scores were generally lower than those for the subjects of the previous experiment. This does not, however, mean that the present subjects were better at tracking since, between the two experiments, some improvements were made in the apparatus with a view to removing an undesirable back-lash in the handle. What can be compared is the improvement of the performance during learning measured in hundredths of the initial score. Considering that there were 27 trials (and not 21 as in the former experiment) it is interesting that this improvement was much less marked in the present case: in the former experiment the best scores were equal to between 4·6 and 10·3 per cent of the initial score while in the present one they ranged from 7·03 to 18·28 per cent of the initial score. It is difficult to judge whether the improvement of the apparatus lowered the high initial scores more than the smaller final ones or whether the learning process of this group was indeed slowed down by a more difficult task presented by two targets instead of one.

The point noted previously that the initial score is a poor indicator of final performance after practice seems to be confirmed e.g. the rank correlation coefficient between the initial score and the average of the last 10 trials was only $+0{\cdot}26$, and the rank correlation coefficient between the first and the last trial was $-0{\cdot}37$.

2.3. *Regression of scores on sensitivities*

The scores varied with sensitivity reaching quite high values when the sensitivity became uncomfortably high or low. As in the earlier experiments, a hyperbolic regression curve of the type

$$S^2 = A\mu + B\mu^{-1} + C \qquad (1)$$

was fitted to the average scores. The averages were taken here over the last 12 trials for each subject and, as before, S^2 was the score measured in squared mils and μ was the control sensitivity measured in mils/sec/degree. The values of the corresponding parameters of the regression hyperbolæ are given in Table 2. The shapes of hyperbolæ were very similar to those obtained previously (cf. Figs. 4, 5 and Table 1 in North *et al.* 1958).

Table 2. The parameters of regression hyperbolae

Subject	A	B	C	$\sqrt{(B/A)}$	$2\sqrt{(AB)}$	$2\sqrt{(AB)}/C$	Mean score for 12 trials
D1	0·6774	66 550	2276	313	425	0·1862	3148
D2	0·6875	70 550	3659	320	440	0·1213	4561
D3	0·8171	48 860	3934	245	400	0·1017	4815
D4	0·8091	138 115	960	413	668	0·6958	2323
D5	1·9108	111 860	3181	242	925	0·2908	5227
D6	0·7542	199 385	1435	514	775	0·5401	3093

The coefficients A and B were of the same order as before, whilst the coefficients C were generally smaller. It is clear from Formula (1) that $\sqrt{(B/A)}$ gives the theoretical sensitivity leading to the maximum score $C+2\sqrt{(AB)}$. For different subjects this theoretical optimum sensitivity varied considerably reflecting individual preferences of the operators and ranged from 243 to 603 in the earlier experiments. Among the present subjects it remained in the interval 242–514. Optimum sensitivity depends, of course, on the input scale and the transformation properties of the mechanical system. In the case of these experiments both were kept constant and the differences may be attributed to the physiological and psychological characteristics of the subjects. Similar differences have been observed in pilots' choices of aircraft control sensitivities. The value $2\sqrt{(AB)}$ measures (cf. North *et al.* 1958, p. 320) the theoretical contribution to the score of errors due to inaccurate handle movements as amplified by the characteristics of the system. These were again smaller, on average, in the present experiment which is understandable in view of the improvement in the design of the control handle already mentioned.

2.4. *Influence on the scores of changing targets*

One of the aims of the present experiment was to find how changing targets influenced the performance of operators. In the last twelve trials six were conducted with the target CHTI and six with the target CHTII. By taking the mean of the six scores for each target and for each sensitivity, 20 average scores were obtained for each subject. The targets were displayed in these 12 trials in the following order:

CHT's: I, II, II, I, II, I, I, II, II, I, I, II;

thus even if the learning were not completed and the subjects were still improving the order of presentation of the targets was such that this factor should have been eliminated.

An analysis of variance led for each subject to a table of the type shown in Table 3. The results for all 6 subjects are summarized in Table 4.

Table 3. Analysis of variance for subject D4

Source of variance	Degrees of freedom	Mean square	Variance ratio
Between sensitivities	9	1 010 920	8·03
Between targets	1	558 760	4·44
Error (residual)	9	125 932	—

Table 4. The results of analysis of variance

Subjects							Significance levels of variance ratio	
Variance ratio	D1	D2	D3	D4	D5	D6	5%	2·5%
Between sensitivities	8·06	1·65	3·44	8·03	9·74	65·7	3·18	4·03
Between targets	6·63	2·98	0·52	4·44	0·60	0·20	5·12	7·21

The variance ratios for ‘ between targets ’ were not significant at the 5 per cent level except for subject D1 for whom it was significant at 5 per cent level but not at 2·5 per cent level. The experiment thus confirms the conjecture that the use of different targets composed of the same harmonics should not influence the score. The variance ratios for ‘ between sensitivities ’ were highly significant except for subject D2 who displayed very small differences in his score with varying sensitivities.

3. EXPERIMENT II

3.1. *Method*

The subjects were again six works apprentices denoted here by E1–E6. They were required to track one of *three* compound harmonic targets (CHTI, CHTII, CHTIII) shown in Fig. 1, the target CHTIII having a velocity given by the formulae:

$$\text{CHTIII: } 0{\cdot}25[\cos(2\pi t/30) - 1{\cdot}5\sin(2\pi t/10) + 1{\cdot}5\cos(2\pi t/5)].$$

The first two targets were those used in the Experiment I. As in Experiment I, the targets were presented in random order. By changing the direction of the cam and by changing the sign of velocity one could obtain four different targets from CHTIII so that one had at one's disposal eight different targets. In the last group of trials they were presented in the following sequence:

*CHTI CHTIII CHTIII† *CHTIII *CHTIII† CHTII CHTII† CHTI

where the * sign before the target denoted the change of sign of velocity and a † sign after the target denoted the change of direction. At each trial only five sensitivities, 50, 125, 300, 750 and 1750, were explored since it was felt that, in view of the results of experiments of North *et al.* (1958) and Experiment I, the hyperbolic regression described adequately the relation between the score and the sensitivities, so that five values would be enough to determine its parameters. To study the influence of the magnification of the error display on the score *four* conditions were explored having magnifications on the display the same as in the experiments previously described and 2, 4 and 8 times as great. Denoting by ν the reciprocal of magnification we can say that there were four values of ν used: 1, 0·5, 0·25 and 0·125. It was expected that with increasing values of ν (i.e. with the error being displayed less and less distinctly) the performance of the operator would deteriorate, and conversely with smaller values of ν the increased magnification would help the operator in assessing the error and compensating for it. This, as will be seen, was confirmed by the results. It was also expected (cf. North, 1954, p. 16) that, with very small values of ν, the magnification of the display would be so exaggerated that the operator would have difficulty in following the spot and that his performance would again deteriorate showing a hyperbolic regression similar to that already described for sensitivities. In order to verify the latter expectation it would be necessary to explore very large magnifications and this would necessitate an apparatus with a much wider display tube. It was found in some pilot experiments that tracking the target with a magnification of 16 was still improving the score, whilst for higher magnifications the operator was not able to ' catch ' the spot at all and the experiment could not be conducted.

Each of 38 trials consisted of two half-trials of five runs each with varying sensitivities and two magnifications. In trials of odd serial numbers magnifications 1 and 4 were applied and in trials with even serial number magnifications 2 and 8 were used. Thus in every pair of trials there were four half-trials with four magnifications each with five sensitivities; the order of presentation of these sensitivities was randomized, remaining however, the same in a pair of trials until the complete set of four magnifications was completed. As before, each run lasted 40 secs, but the results of the first 10 secs were not recorded. The instructions given to the subjects were almost identical with those given in Appendix to North *et al.* (1958), but it was explained that the magnification of the target would be changed every half-trial and that they should not unduly worry, since the machine would register the ' real ' errors and not the ' apparent ' ones magnified on the display tube. At the beginning, the subjects had difficulties in ' catching ' the spot for high sensitivities and high magnifications but these difficulties were overcome with practice.

3.2. *Learning Results*

It was impossible to draw a single ' learning curve ' since, with the change of magnification, the scores were not comparable. For the same reason, it was impossible to compare the results of learning this task with those of the previous experiments. The learning curve displaying the average scores for the 19 half-trials with $\nu=1$ had a shape similar to that of the learning curve described by North *et al.* (1958), but one has to bear in mind that here each half-trial was followed by three half-trials with increased magnifications of error display and that there must have been a considerable transfer of skill which helped the next half-trial with $\nu=1$. One thing was clear; it was necessary to prolong the learning period to 38 trials in order to achieve reasonable stability of score between successive trials. In other words, the learning was slower, but this could have been expected since the subjects were coping with a much more complicated task of tracking eight different targets (or three if the symmetries were disregarded) not only with changing sensitivities but also with changing magnification of display. On the other hand the transfer of skill was considerable since e.g. for $\nu=1$ steady performance was achieved in 19 half-trials (95 runs) whilst it required 22 full trials (220 runs) in the experiments reported by North *et al.* (1958) and 27 full trials (270 runs) in Experiment I.

3.3. *The influence of changing magnifications on the scores*

In the last 16 trials there were 8 half-trials executed with each of the four magnifications. The average scores for these four groups of 8 are given in Table 5.

Table 5. Mean scores for various magnifications

Subject	$\nu=1$	$\nu=1/2$	$\nu=1/4$	$\nu=1/8$	Mean
E1	3507·2	2259·3	1800·2	1358·5	2231·3
E2	4173·3	2760·2	2901·1	2428·5	3065·7
E3	3210·1	1882·6	1355·3	916·7	1841·2
E4	3418·3	2520·9	1839·9	1559·7	2334·7
E5	3596·6	1842·2	1475·9	1132·8	2011·9
E6	3535·8	1962·2	1953·9	1207·7	2164·9

With the increasing magnifications the scores decreased; and the decrease was very nearly linear when plotted as a function of ν (cf. Fig. 2 for subjects E1–E4). This result does not contradict the expectation mentioned earlier that with much smaller values of ν the performance would again deteriorate, since it might be that for smaller values of ν the curve would turn to the right, but that in the range of ν-values explored, we were still investigating the values situated near the asymptote of the hyperbola.

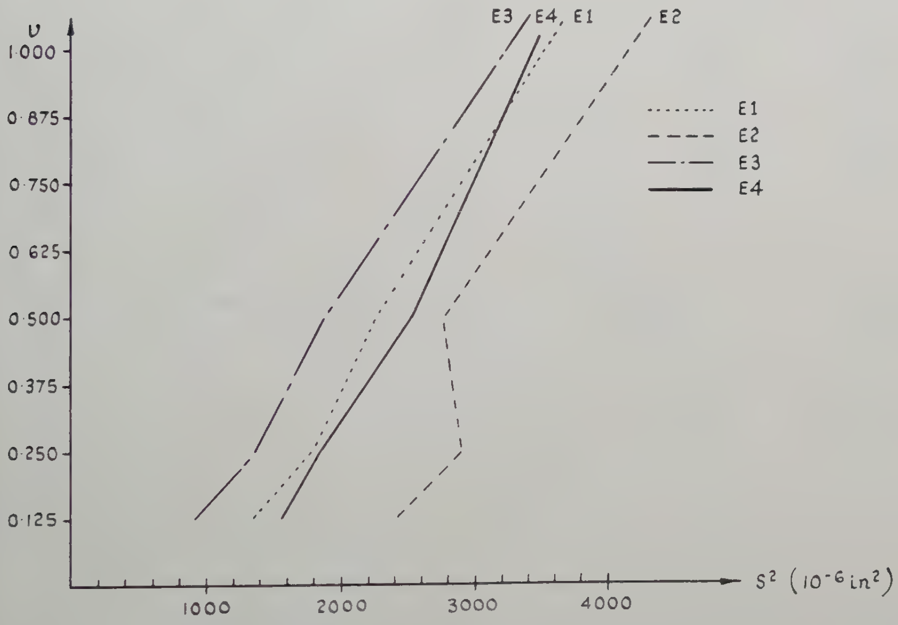

Figure 2. Dependence of mean scores on magnification.

3.4. *Regression of scores on sensitivity for various magnifications of error display*

As in the previous experiments, a hyperbolic regression curve of the type given by Formula (1) was fitted to the average of the last 8 half-trials for each magnification and for each subject. Corresponding values of the parameters A, B and C of the regression curves are given in Table 6. It should be borne in mind that whilst the similar parameters in Table 1 of North *et al.* (1958) were based on 100 runs (10 trials each of 10 runs) and in Table 2 of the present paper on 120 runs (12 trials of 10 runs each) those in Table 6 were based only on 40 runs (8 half-trials of 5 runs each) so that the values of coefficients are less reliable.

Table 6. The parameters of regression hyperbolae

Subject	$\nu=1$			$\nu=1/2$			$\nu=1/4$			$\nu=1/8$		
	A	$B.10^{-3}$	C	A	$B.10^{-3}$	C	A	$B.10^{-3}$	C	A	$B.10^{-3}$	C
E1	1·33	50	1716	0·65	47	1556	0·83	82	765	0·64	43	689
E2	0·66	95	3147	0·63	51	2050	1·47	101	1369	1·05	91	1199
E3	1·73	143	1230	1·38	50	694	1·17	45	359	0·56	24	426
E4	1·54	59	2102	1·26	4	1746	1·25	14	1001	1·34	36	521
E5	0·02	141	2645	0·19	80	1191	0·52	91	563	0·54	50	477
E6	0·83	198	1727	0·65	96	936	1·02	110	613	0·65	66	384

The four regression hyperbolae for subject E4 are shown in Fig. 3 and similar curves were obtained for the remaining subjects. Comparing the first three columns of Table 6 with those of Table 2 we see that the results are very similar (with the exception of subject E5 who showed an extremely small value of A), the values of C being on the average smaller than in Experiment I.

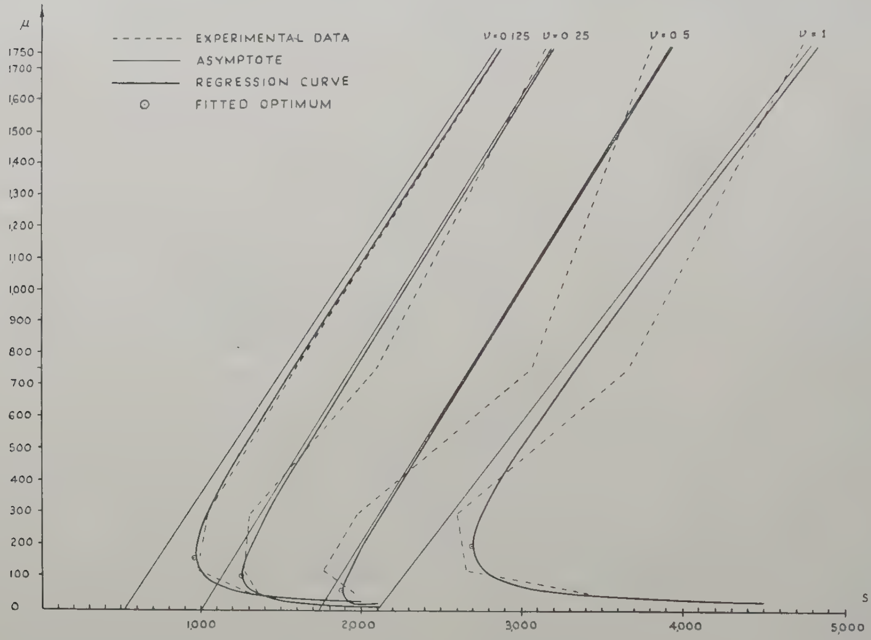

Figure 3. Regression of scores on sensitivity for subject E4.

With increasing magnification, the curves were shifted to the left and generally the values of C decreased. Since C may be interpreted as the contribution of the systematic error and of the visual error in judging the display this is what would be expected. Plotting C against ν for each subject, in the same way as in Fig. 2, one can easily see that this relation was very nearly linear. There was no clear dependence of A or B on magnification, the only exception being the above-mentioned subject E5. The theoretical optimum values of μ, i.e. $\sqrt{(B/A)}$ calculated for different magnifications also showed no regular dependence on ν (again with the exception of subject E5). Thus one is led to assume that the differences of shape of various regression hyperbolae were chance effects and that the situation may be adequately described by regression hyperbolae of the same shape having for different magnifications linearly varying values of C. The admissibility of this hypothesis is discussed in the next paragraph.

3.5. *Analysis of variance*

For each subject the last 16 trials consisted of 160 runs which could be classified in three ways: 8 half-trials each with one of the 4 magnifications and each consisting of 5 runs with varying sensitivities. In order to study the influence of these three factors on the scores, an analysis of variance was made of the type shown in Table 7. The variance ratios for the different subjects are set out in Table 8.

Table 7. Analysis of variance for Subject E4

	Degrees of freedom	Mean square	Variance ratio
Between trials (T)	7	1 570 231	3·60
Between magnifications (M)	3	27 391 067	62·76
Between sensitivities (S)	4	21 700 808	49·72
Interactions:			
$M \times S$	12	283 827	0·65
$T \times M$	21	685 290	1·57
$T \times S$	28	742 196	1·70
Residuals	84	436 447	—

Table 8. The results of the analysis of variance

Subject	Trials (T)	Magnifications (M)	Sensitivities (S)	$(M)\times(S)$	$(T)\times(M)$	$(T)\times(S)$
E1	3·04	72·11	18·30	1·57	1·87	1·35
E2	16·02	25·18	10·72	0·87	2·25	0·62
E3	6·48	78·79	26·00	2·19	2·66	0·75
E4	3·60	62·76	49·72	0·65	1·57	1·70
E5	7·23	126·88	31·64	4·76	2·65	1·95
E6	9·38	97·30	41·29	4·94	1·35	1·63
5 per cent points	2·14	2·73	2·50	1·88	1·71	1·63
1 per cent points	2·89	4·06	3·59	2·44	2·11	1·93

The significance of differences between magnifications and between sensitivities shown by extremely significant values of variance ratio for these variables was expected: there are however significant differences of scores between trials. This may be ascribed either to the fact that the learning process was not quite terminated by the beginning of the last 16 trials or to the presentation of different targets in successive pairs of trials. In view of the results of Experiment I, where the targets did not influence the scores, the former conjecture appears more likely.

For the first four subjects the interaction between the magnifications and sensitivities was negligible and for these subjects it may be assumed that the score consisted of a part dependent on sensitivity and a part dependent on magnification; in view of the results dicussed above this regression surface of scores on μ and ν appeared to be of the form:

(2) $$S^2 = A\mu + B\mu^{-1} + C_1\nu + C_2$$

within the range of explored μ and ν values. For the remaining two subjects the analysis of variance did not confirm this hypothesis, but it must be borne in mind that the existence of a significant interaction does not always imply interaction in any real sense (cf. Kendall, 1946, p. 189) and that the scores of subject E5 were exceptional in many other respects.

§ 4. EXPERIMENT III

4.1. *Method*

In all the foregoing series of tests the human control was exerted by the movement of a control handle. In these *isotonic controls* the force required to move the handle was extremely small (of the order of 1 ounce) and was independent of the position and the velocity of the handle. To investigate the results of tracking with *isometric* controls, the apparatus was modified so as to present a very high stiffness and an extremely small movement of the handle.

The handle was coupled to one end of a torque tube which was designed to allow 2° of deflection for a maximum force of 100 lbs pull with one hand and 100 lbs thrust with the other exerted at a radius of 4·5 in from the handle centre. The lower end of the torque tube was rigidly clamped. An angular transducer was fitted to give a signal proportional to twist and the electrical signal from the transducer was amplified to a suitable level for feeding to the computer. The control sensitivity was determined by loading the handle with weights and measuring the output volts/lb of applied force. From this ratio and from the known constants of the computer the sensitivity measured in thousandths of an inch mils/sec/pound was determined. Sensitivities are referred to force rather than torque, but as the radius of application was always 4·5 in, the conversion is straightforward.

The subjects were six works apprentices denoted by F1–F6. The first three subjects were new, but subjects F4, F5 and F6 had taken part exactly a year earlier in Experiment II and were then denoted as E6, E5 and E2 respectively.

The velocity control of the type described was used with CHTII as the target. Each trial consisted of 10 runs, each run lasting, as before, 40 secs of which the first 10 secs were not recorded. Pilot experiments showed that the operator could cope with a much larger range of sensitivities than in the isotonic case and in each trial the following 10 sensitivities (measured in thousandths of an inch mils/sec/pound) were explored:

22·5 45 72 112·5 225 450 1125 2250 4500 9000

Thus while the ratio of the lowest to the highest sensitivity was 1 : 50 in the experiments of North *et al.* (1958) and Experiment I, and 1 : 35 in Experiment II, it was 1 : 400 in this experiment. In each trial the sensitivities were presented in random order. The total number of trials was different for various subjects (see Table 9), since some subjects approached equilibrium quicker than others. The instructions given to the operators were similar to those shown in the Appendix to North *et al.* (1958) with the difference that the operators were told to *press* the handle in the desired direction (and not to *turn* it as in previous instructions), and it was explained to them that the sensitivities would be changed from one run to another so that different forces would need to be applied in order to compensate for errors.

4.2. *Learning Results*

The score assessing the performance of the operators in each trial was the mean over all 10 runs of the squared error measured in square mils. The learning curves for the ‘ new ’ and ‘ old ’ subjects were distinctly different: those for one ‘ old ’ and one ‘ new ’ subject are shown by way of example in Fig. 4. The changes or scores with learning are given in Table 9, from which it can be seen that the ‘ old ’ subjects had a considerably lower initial score than the ‘ new ’ ones, their final score was generally lower and they reached their ‘ equilibrium ’ after a smaller number of trials. Thus in spite of the fact

Table 9. Changes of scores with learning

Subject	F1	F2	F3	F4	F5	F6
Initial score	82 318	13 687	28 673	7546	3781	6525
Total number of trials	30	27	28	16	15	19
Best score	2975	1552	1693	1132	1090	1394
attained in trial number	28	21	23	13	12	17
Mean score for last 10 trials	3242	1695	2000	1564	1340	1764

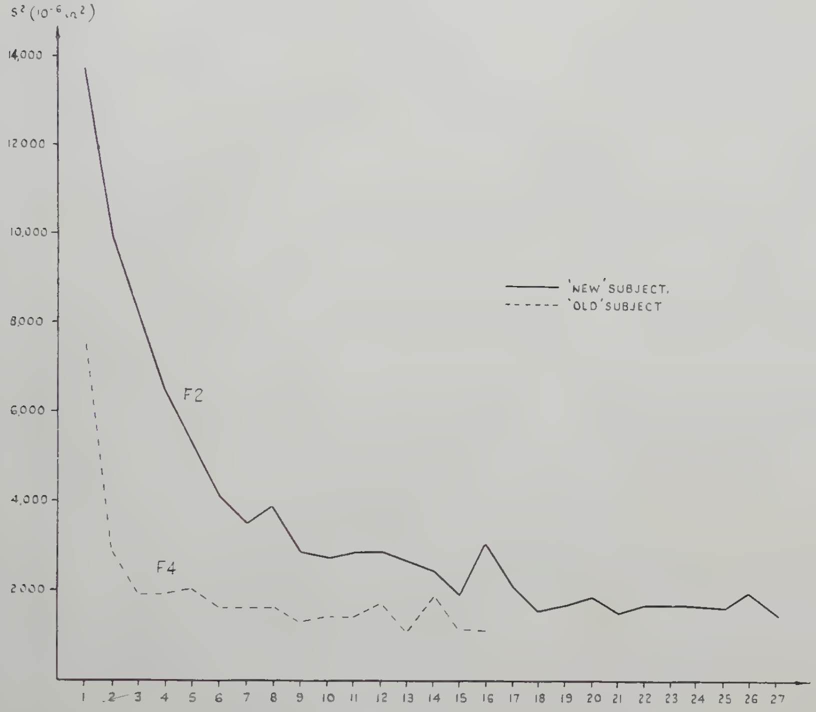

Figure 4. Changes of scores with learning.

that a whole year had elapsed since they had taken part in tracking experiments and these had been with isotonic controls the subjects showed a rapid transfer of skill in tracking with isometric controls.

4.3. *Comparison of scores in isotonic and isometric tasks*

Since subjects F4–F6 took part in the Experiment II with isotonic controls it was possible to compare results of tracking with the two types of control. Although sensitivities in these two cases were expressed in different dimensions, comparable data were given by the scores for optimum sensitivities. In Experiment II the optimum sensitivity was assessed for each subject from the last 8 half-trials conducted with magnification 1 and the optimum mean square error (m.s.e.) or root-mean-square error (r.m.s.e.) was compared with the corresponding optimum score in the last 10 trials of Experiment III. The results are given in Table 10, which shows that the isometric ‘ pressure ’ controls led to performances with r.m.s. errors about half of those in the case of isotonic controls. Similar results were obtained by Gibbs and Baker (1952), but in their experiments the ratio was about 0·80 instead of about 0·53 in our case. A *considerably more pronounced improvement* in our

Table 10. Comparison of scores for isotonic and isometric tracking

Subject	F4=E6	F5=E5	F6=E2
Isometric controls:			
Optimum sensitivity	225 (373)	450 (310)	72 (318)
mean square error (in mils^2)	716 (719)	763 (694)	1071 (1159)
root mean square error (in mils)	26·8 (26·8)	27·6 (26·3)	32·7 (34·0)
Isotonic controls:			
Optimum sensitivity	750 (489)	300 (2401)	300 (385)
Mean square error (in mils^2)	2604 (2553)	2664 (2763)	3583 (3649)
root mean square error (in mils)	51·0 (50·6)	51·6 (52·6)	59·9 (60·4)
Ratio of root mean square errors	0·525 (0·530)	0·535 (0·500)	0·546 (0·563)

Numbers in brackets give the theoretical optima from the corresponding regression hyperbolae. See below, para 4.4.

experiments may be partly explained by the fact that, in the experiments of Gibbs and Baker, results were still being affected by learning (cf. their Fig. 3) and the estimation of the optimum sensitivities was not as accurate as in our experiments—it is clear that by comparing the optimum performance in one case with a non-optimum in another distorted results could be obtained.

It would be presumptuous to assert that, under different experimental conditions the same marked improvement of performance would still obtain, but the data shown in Table 10 indicate that isometric controls can be usefully applied at least in situations in which the operator works under conditions similar to those of our experiments.

4.4. *Regression of scores on sensitivity*

As in the isotonic case, the scores increased when the sensitivities were very large or very small and a hyperbolic regression was fitted to the averages of the last 10 trials. The results are given in Table 11; the experimental data and the fitted regression hyperbolae for one 'new' and one 'old' subject are given in Figs. 5 and 6. Subject F6 was chosen since for this 'old' apprentice the experimental curve displayed two marked optima (for $\mu=72$ and $\mu=450$). There was a trace of the same phenomenon in the data for the 'old' subject F5, while for the remaining subjects the experimental curves were similar to the curve shown in Fig. 5. It is interesting that two optima were also obtained in some pilot experiments with operators who had previously extended practice with isotonic controls (e.g. with one of the present authors). If introspection may be allowed, the subjective feeling during the tracking was that for high sensitivities the tasks were very similar in both isotonic and isometric cases. It was when passing to smaller sensitivities that the difference between 'moving' and 'pushing' the handle became very marked. Thus it may be that the transfer of skill occurred more readily for higher sensitivities and less so for lower ones, which would explain the observed phenomenon. Most probably this would disappear with practice.

Table 11. The parameters of regression hyperbolae

Subject	A	$B \,.\, 10^{-3}$	C	$\sqrt{(B/A)}$	$2\sqrt{(AB)}$
F1	0·221	29·03	2564	362	160
F2	0·232	16·39	1122	266	123
F3	0·295	20·32	1276	262	155
F4	0·353	49·01	456	373	263
F5	0·310	28·21	513	310	187
F6	0·284	28·69	978	318	181

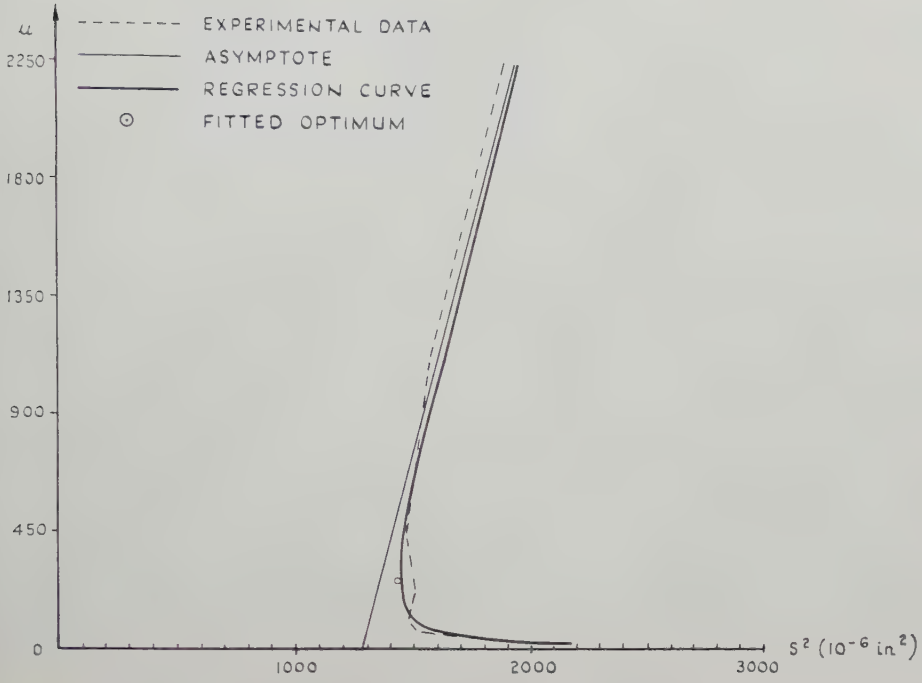

Figure 5. Regression of scores on sensitivity for subject F3.

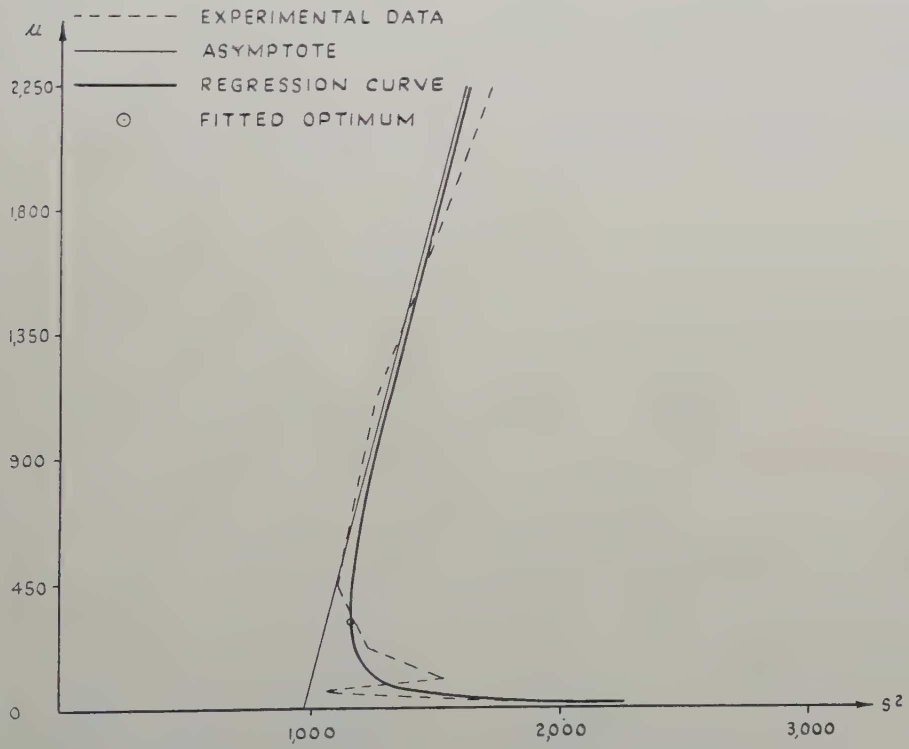

Figure 6. Regression of scores on sensitivity for subject F6.

One of the features of the regression hyperbolae in this series is a relatively small variability in the slopes A of the asymptotes (cf. Tables 2 and 6). The values C are smaller for the ‘ old ’, more experienced subjects. The quantities $2\sqrt{(AB)}$ may be regarded as contributions due to inaccuracies in the handle movements (or pressures exerted on it) to the total squared error and they are conspicuously smaller for isometric controls than for the isotonic ones. The observed improvement of performance may be due either to a greater accuracy in applying the appropriate *force* to the handle than in performing the appropriate handle *movement*, or to the difference in amplifications which these basic errors undergo in passing round the control loop (cf. North 1952) or to both. The amplification of the variance of basic errors in the velocity control is proportional to the square of the delay in the loop. Gibbs and Baker (1952) suggested a substantial reduction of this delay in the case of isometric controls which is possibly due to the change of the effective mechanical impedance.

In many practical systems, when a human operator is included in a control loop, the control devices have some self-centring provided by a spring. The results presented here show that, under the conditions of our experiments, the infinite-rate spring is preferable to a zero-rate. The cases of different finite stiffnesses of the control remain to be explored.

The control sensitivity may be represented by the diagram of Fig. 7. The length of the vector from the origin to any point on the diagram gives a measure of the sensitivity, and the tangent of angle α is the spring rate.

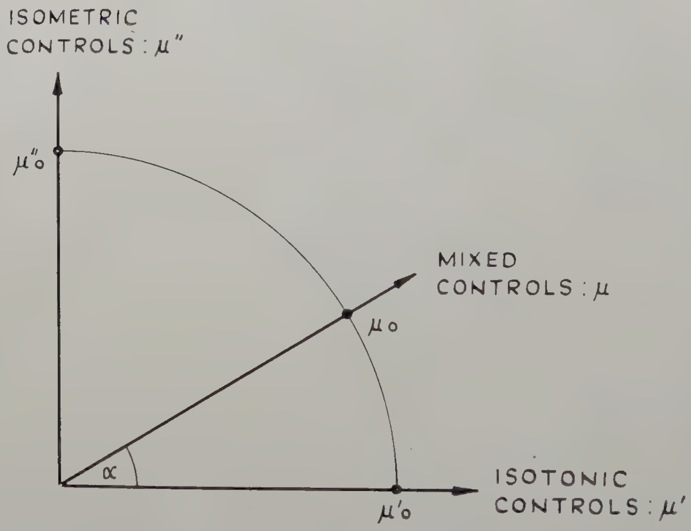

Figure 7.

For any given spring rate we expect to be able to find an optimum value of the sensitivity, and the locus of the optimum sensitivities is of interest. One would expect that the tangents to this locus would intersect the axes perpendicularly as it seems reasonable that the results for very low and very high values of stiffnesses should be indistinguishable from those for the limiting cases. A reasonable locus would therefore be an ellipse which can be reduced to a circle by proper choice of units on the axes. In order to verify this conjecture it would be necessary to carry out further experiments with self-centring springs of different stiffnesses and further work on these lines is contemplated.

The authors wish to acknowledge the assistance of Mr. H. J. Clark of the Research Section, Boulton Park Aircraft Ltd., who not only was responsible for the modifications to the apparatus and its proper functioning during the experiments but also was most helpful in the design of the experiments by taking part in a number of pilot experiments and by discussing with the authors the ways in which a full use of the possibilities of the apparatus could be made.

Il est rendu compte de 3 expérimentations ayant pour objet la sensibilité des organes de commande dans des tâches de pistage à l'aide du même dispositif que celui de North *et al.* (1958).

Les résultats de la première expérience ont confirmé ceux précédemment établis par North *et al.* en ce qui concerne l'influence d'un changement de la sensibilité des organes de commande sur la précision de la performance. Cette expérimentation diffère de celle primitivement rapportée, par l'utilisation de deux cibles différentes, se déplaçant selon les mêmes harmoniques, mais avec déphasage.

Dans la seconde expérience, on a étudié la manière dont l'amplification variable du signal et la sensibilité variable de la commande influencent conjointement la précision.

Dans la troisième expérience, on a exploré le pistage à l'aide d'organes de commande isométriques: dans ce type de commande, l'erreur est compensée, non par les libres mouvements de la poignée, mais par les forces variables exercées par l'opérateur sur les commandes pratiquement sans déplacement de la poignée.

On a trouvé que la performance avec ce type de contrôle était supérieure à celle qu'on obtient avec des contrôles isotoniques.

Dans les 3 expériences on a étudié les effets de l'apprentissage, aussi bien que la performance quand l'apprentissage semblait être plus ou moins complet. On a observé un cas intéressant de transfert d'habileté après une interruption d'une année, sans aucune pratique intermédiaire.

Es werden 3 Experimente über die Steuerungs-Empfindlichkeit bei kompensatorischen Spur-Halte-Versuchen beschrieben, in denen der gleiche Versuchsapparat benutzt wurde wie von North *et al.* (1958). Die Ergebnisse des ersten Experimentes bestätigen die Befunde der zuvor von North *et al.* berichteten Resultate über den Einfluss von wechselnder Steuerungs-Empfindlichkeit auf die Genauigkeit einer Leistung. Dieses Experiment unterschied sich von dem vorher genannten durch die Anwendung von 2 verschiedenen Spuren, anstelle einer einzigen, die bei gleichem Verlauf phasenverschoben waren.

Im zweiten Experiment wurde verfolgt, in welcher Weise eine verschiedene Vergrösserung der Darbietung und eine verschiedene Steuerungs-Kontroll-Empfindlichkeit zusammen die Genauigkeit beeinflussten.

Im dritten Experiment wurde Spur-Halten mit isometrischer Steuerung untersucht: bei dieser Steuerungsaufgabe wurde der Fehler nicht durch freie Bewegungen des Griffes kompensiert, sondern dadurch, dass der Arbeiter wechselnde Kräfte, praktisch ohne Bewegungen, auf den Griff ausübte. Die Leistung mit dieser Steuerungsart war besser als diejenige mit isotonischer Steuerung.

In allen 3 Experimenten wurden die Lerneffekte neben der Leistung untersucht. Ein interessanter Fall zeigte, dass die bei isotonischer Steuerung erlernte Geschicklichkeit noch nach einem Jahr das Erlernen der isometrischen Steuerung beschleunigte.

REFERENCES

GIBBS, C. B. and BAKER, J. C., 1952, Free moving versus fixed control levers in a manual tracking task, pp. 467–472 in Tustin (ed.) *Automatic and Manual Control* (London: Butterworth's Scientific Publications).

KENDALL, M. G., 1946, *The Advanced Theory of Statistics*, Vol. II (London: Charles Griffin & Co.).

NORTH, J. D., 1952, The human transfer system in servo systems, pp. 473–494 in Tustin (ed.) *Automatic and Manual Control* (London: Butterworth's Scientific Publications); 1954, The rational behaviour of mechanically extended man, Conference on Human Operator in Control Systems, Royal Military College of Science, Shrivenham, Wilts.

NORTH, J. D., LOMNICKI, Z. A., ZAREMBA, S. K., 1958, The design and interpretation of human control experiments, *Ergonomics*, **1**, 314–327.

Editorial Note.

The Editors are glad to announce that this Journal was adopted as the official publication of the International Ergonomics Association at a meeting held on 23 August 1961 in connection with the First International Congress of the Association at Stockholm (see *Ergonomics*, **2,** 400 ; **3,** 84, 380).

The Articles of Association, the Minutes of the first meeting of the General Assembly and the papers delivered at the Congress will be printed in the January 1962 number, and subsequent issues will include items such as official notices and lists of members.

The Journal will, of course, continue as hitherto to act as the official publication of the Ergonomics Research Society.

BOOK REVIEWS

Problems of Progress in Industry. (London : H.M.S.O.)

The ten booklets in this series that have been prepared so far by the D.S.I.R. on "Problems of Progress in Industry" are not a record of a predetermined plan of investigation, but are based on a series of research projects carried out independently in various centres.

Men, Steel and Technical Change. (Dept. of Social Science, University of Liverpool.) 2*s.* 0*d.* No. 1.

The process of transformation from the older technique of control by experience and tradition to that by scientifically trained management is described. Working with higher precision machinery and modern instrumentation demanded scientific and technological skills as well as sound judgment and experience. This change from traditional management to management with scientific outlook was effected with comparative ease, but was a most striking and vital one.

For the productive workers their objective was unchanged—though their responsibilities of control and consequently their mental effort were increased. Redundancy was eased by increasing demand for the company's production. To some workers there were benefits ; sacrifices required from others. The problems were solved largely through the good relations between employer and trades union.

A generation ago the influence of Chapel was credited with the reasonableness and statesmanship of Labour leaders. But in the earlier days employer and worker sat side by side in those institutions breeding regard for individuality and personal prestige on both sides. Burke said "Government with progress and order needs regard for convenience and custom". Principles of this character played a large part in bringing difficult and hard bargaining to a successful issue.

Increase in automation did not destroy craftsmanship, for maintenance men moved to a higher standard of skill, for which they asked and received due recognition.

Managers of Tomorrow. By Rosemary Stewart. 2*s.* 6*d.* No. 2.

The human factor in management was explored by interviewing 3,000 managers and reviewing 51 companies each employing over 10,000 people. The vagaries of human nature and the widely differing views on management made simplification impossible and the review is a descriptive account of the varying practices adopted.

Too large a proportion of the firms are not sufficiently conscious of the problem to plan for selection and training. Where there is a plan open and fully recognized, support should be forthcoming from top management, and the members of staff involved should be kept frankly and correctly informed of their progress. The author does not seem to give sufficient weight to an important factor after the junior stage is passed, that of experience. Men are not engaged by firms to be trained, but to do a job of work. Training results in increased efficiency, and Napoleon, it is said, asked of his generals that they should win battles. Likewise it is asked of salesmen that they book orders, and if in addition to their success in this they can infuse others with their enthusiasm and skill, it will be a valuable factor for promotion to top rank.

The report points out that more accountants and secretaries rise to top rank than do engineers. This important observation should be more fully investigated. It surely must hold a valuable lesson.

Management and Technology. By Joan Woodward. 2*s.* 6*d.* No. 3.

What is the standard of management in our industries, their weakness, and their strength ? If a concerted attempt to increase efficiency and productivity is to be made by the application of scientific method, it is essential we should understand the present position.

The author of this pamphlet has made a praiseworthy beginning by an analytical examination of a hundred firms in an area of South East Essex. A large amount of information was collected and the author has tried to put so much in this review that the reading of it demands careful attention. To organize the information an effort was made to associate it with line and staff relations, and later to types of industry, but no correlation was established. Eventually a valuable contribution was made by a classification of industries related to technical complexity and showing characteristic patterns of organization, with a further relation to business success and good human relations.

To secure the confidence of industry the author urges confirmation and criticism by an extended series of similar investigations, and to guard against rigid rules and systems the reader is left in no doubt of the essential importance to be attached to systematic analytical investigation conducted by trained scientific staff.

In discussing measurement of efficiency the author has a mixed bag of factors. This subject has had the attention over a number of years of an international conference of accountants, and others highly qualified. Their results have been used for inter-firm comparisons, and provide a valid assessment standard of expert character.

It is to be hoped that the author's suggestion for further studies will receive sympathetic and urgent consideration.

What They Read and Why (The Use of Technical Literature in the Electrical and Electronics Industries). By Nigel Calder. 2*s.* 0*d.* No. 4.

A good management structure demands good managers and good managers require good assistants. Nigel Calder gives a summary of the research which sought to find out whether indeed industry was being served by good technologists. Industry being represented by 127 firms in the electrical and electronic section.

What constitutes a good technologist ? The author's test is unique and interesting: " Cautious analysis of the evidence suggests that the habit of referring to literature in solving a problem appears to be one of the characteristics which make a good technologist ". Accepting this test the result is not encouraging. At the top is the highly trained research worker, then although a bad second, come managers, with their assistants of all grades below the manager. Not one in six, says the writer, goes near the library, and in firms that have a library less than half the technologists use it. The review is outspoken and frank, " and much of the explanation must be sought within the technologist himself and in his training ".

As you can no more indict a class than a nation, the training would appear to take the brunt of the responsibility. Whose business is it to give attention to the seriousness of this conclusion ?

Human Problems of Innovation. By Honor Croome. 2*s.* 6*d.* No. 5.

When research is aimed to provide new processes or products for development by a non-scientific management, it can almost safely be said that sooner or later failure will result, certainly there will be failure to achieve the best results. This review is a study of the experience of several firms with an interest in research, seeking new enterprises and new markets. Success comes to the firm realising it must think scientifically about the whole job and finding that good communications between all grades of personnel are achieved not only by the spoken word, but by the spoken word as between equals. In the author's words, " there was achieved a code of mutual good manners expressing a spirit of co-operation and appreciation ".

How this was achieved is told in the booklet in a readable and simple way.

Training Made Easier. 2*s.* 0*d.* No. 6.

In the description of a series of studies in training, the approach to the task is akin to that from which time and motion study developed in the earlier stages of management development. In both cases the job was analysed into its constituent parts, but in the studies under review the analysis has been done in more detail and specifically for the development of training methods. The practice of industrial psychology has been utilized to facilitate learning by the trainee, and in the application of the results considerable success has been achieved. The importance of a specialist with psychological training is stressed as a necessity in the designing and introduction of a scheme. This may call for co-operative efforts by industrial organizations, and may limit the adoption of the proposals. The pamphlet somewhat plaintively says, industry as a whole has not shown much interest in developing training methods. This is very far from being the only case of science going faster than industry is willing to follow and it is pertinent to ask why this should be so.

It is interesting to observe that the work which led to time and motion studies was certainly intended as a basis for training methods. Why was that so fruitful and widespread in its application by industry, while related research under review in this booklet raises so little industrial interest? It is an important question that deserves the attention of those responsible. Who provides money to pay for research for industry without knowing that industry wants it ?

The Older Worker and His Job. By Hilary M. Clay. 1*s.* 3*d.* No. 7.

It is in the best interests of industry that its social obligations should not be neglected. Not only from the humanitarian point of view, but also from the fact that widely varying conditions of social obligations carried by European industries in their wages systems make it very desirable to know how those conditions can be satisfied in the most economical manner. Further it is valuable to retain the worker's individuality by making the position one which is earned and not just that of charity however well intentioned.

In this study the author has brought together some useful results of research into the effects of ageing on various jobs. As so often in these investigations it is the unexpected that happens. It might well be thought that the difficulty the older worker would find would be related to physically heavy tasks. But it is found that it is the problem of speed and keeping in step that constitutes the problem, and if this is dealt with satisfactorily other difficulties can be brought into line. The learning of a new job can be eased by properly considered schemes.

The immediate problem is that of interesting industry to support and give facilities for further research under the working conditions and stresses of industrial life.

Ergonomics of Automation. By A. T. Welford. 3*s.* 6*d.* No. 8.

Automation and Skill. By E. R. F. W. Crossman. 3*s.* 6*d.* No. 9.

Machinery invention and its progress was largely due to intuition and native wit, haphazard in its timing, and not proceeding by a process of ordered thinking. Science, which is essentially ordered and systematic, given to measurement and definitions, found its greatest successes in the material world best suited to its technique. It was natural that it should find its place in industry, supplementing and directing if not replacing the earlier intuitive efforts. With science developing into fields relating to human experience and capacities, a new possibility of ordered criticism is developed which the earlier " native wit " methods did not encourage, so that with reason and logic science is improving on the earlier efforts. Groups have gathered who by reason of their training, are able to bring disinterested and critical valuation of industrial practice in all its activities.

One of the results of such consideration is to draw attention to the essential part played by the worker, and the necessity, therefore, of considering human body and brain in the designing of new machines, new instruments, etc. This may seem a somewhat obvious comment, but it has required the critic not only to emphasize its importance but to bring in new disciplines of physiology, anatomy and psychology to give body and direction to the efforts.

The information in these two pamphlets tends to overlap, though Welford gives more description of the means employed to facilitate ease and accuracy of control in automatically working plants, while Crossman draws attention rather to the fact that while science has contributed so largely to the development of automation, the intuitive faculties of the operator are invaluable. " Yet oddly enough the operator can sometimes achieve better results than the engineer." Contributions are drawn from a wide variety of sources. Continuous processing of margarine, animal foodstuffs, liquid oxygen, organic solvents, cardboard mill, automatic weaving, cigarette and glass industries, and hot steel strip mills. Welford gives examples of presentation of information particularly on the reading of scales in instrumentation and arrangement of contacts on control boards for the railway and electrical industries, while engineering is represented by automatic milling, drilling and cylinder block machining. The booklets are well supplied with diagrams and photographic reproductions from industry.

Both writers take the view that many of the fears of automation are unlikely to materialize either in redundancy or loss of operators' skills.

Woman, Wife and Worker. 2*s.* 0*d.* No. 10.

This contribution comes from the London School of Economics. The research was carried out within one firm and is clearly of a limited character against the background of the national employment of women. Nevertheless the research team felt itself able to make some generalizations. The views of social reformers of two generations ago that the employment of women was a social evil to be wiped out, are now accepted as unreasonable. Blake's picture of " dark satanic mills " has belaboured the facts too long.

The possibilities that extra earnings can buy desirable amenities—to own a new house, better education, real holidays by sea or country has driven away the dark picture of " keeping the wolf from the door ". Although the review does not specifically mention it, the reduction from 50–55 hours to a standard 40 hours a week makes part time shift work possible as an addition to work at home.

These studies are concerned with problems of management and it is desirable to put them in a right perspective. Such problems are not the sole concern of industry, they are inherent in every form of joint or co-operative effort whatever its purpose and without management no such efforts are possible. It was the regimentation of labour by the industrial revolution that brought recognition of it to all associated with industry, nevertheless it is of universal interest and of corresponding importance. Failure to delegate authority in a rightful way may be the most important single cause of management failure.

The initiative by which management created a vast industry and immense wealth out of the inventions of the Industrial Revolution has to-day spent much of its impetus. These studies are practical and effective proof that if industry can indoctrinate itself with the scientific approach and practice of systematic analysis, new opportunities will be disclosed and clearer thinking will enable much of the vigour and force of that initiative to be regained.

In the growth of industry, management was taken for granted, while simultaneously science confined itself to the exact sciences. Both failed to realize the need for humanistic studies, but as by a common impulse both have realized the case for a new assessment, industry to understand management and science to its study of the so-called human sciences of psychology, physiology and so forth.

Ergonomics, as this attitude of mutual help is called, offers a new opportunity to bring science and industry into a right relation with each other, an opportunity that ought not to be missed. These "human sciences" do not have the definitive character of exact sciences, but they are none the less scientific. It is necessary that this should be said, for some students of exact science criticize their value. In the context of these studies they are the very pith and marrow of the situation.

Much exhortation and example have been spent in persuading an industrial appreciation of science, but the weakness of exhortation is the lack of the mental equipment needed to understand the appeal and make the necessary changes. That lack must be attributed to the failure of public opinion to assess the value of science when present day management was beginning its career. Some effort more personal in its character is essential to help the industrialist to identify his own problems and to understand in his own language their solution.

Forty years ago under Government initiative, non-scientific industries developed their own centres of scientific research and since then they have been creating welcome support for scientific and technological research. Personal contacts have been established with rank-and-file, and working organizations have grown. If these new studies could be effectively associated and openly linked with this atmosphere, an open door would be available for their ready reception. It would provide a valuable opportunity on a scale wide enough and practical enough for the principles of ergonomics, that is the value of the human contribution, to prove themselves. It was the merit of the Industrial Revolution that it worked miracles, reduced costs and increased wages, reduced prices and increased profits. This must still be industry's goal, and if a high standard of efficiency is to be achieved there must be development of machines and men, technology and management. If the Government influence that encouraged research associations were given to persuading industry and particularly trade associations to lend themselves to such an effort, a great stride forward would have been made.

It is one of the outstanding contributions of Joan Woodward's research that industry on an extended area was investigated. The urgency of the national situation for higher efficiencies demands also a wide ranging vision. When Lincoln was surveying his great campaign he said, "If we could just know where we are, and whither we are tending we could better judge what to do and how to do it". Such words would be a fitting prelude to a vigorous effort to give these studies and others like them the usefulness they deserve.

N. G. McCulloch.

Teaching Machines and Programmes. A Bulletin prepared by the Department of Psychology, University of Sheffield. June, 1961.

The first issue contains articles by Annett, Kay and Sime reprinted from 'Discovery' and by Pask from 'New Scientist' both of which appeared early in May. These serve as a useful introduction for the reader coming to the subject for the first time. Other sources of more detailed information are listed since these have not been easily obtainable in this country and there is a short review of two books, one of which contains a comprehensive series of articles published up to June 1960. Ten teaching machines which are commercially available are described and prices given.

More than 100 programmes have now been written. Over 40 are commercially available and these are listed with publishers and prices.

A section on activities in this country includes work at Aberdeen by Leslie Reid, at Bangor by T. R. Miles and D. J. Stewart, at Glasgow by K. Richmond, at Sheffield by J. Annett, K. Austwick, H. Kay and M. Sime, and by Gordon Pask of System Research Ltd. in collaboration with Solartron Electronics. Attention is drawn to Symposia to be held at the British Association at Norwich in September and the International Congress of Applied Psychology at Copenhagen in August.

Further issues of this bulletin will appear if the demand continues and as further information becomes available. Notes on activities in this country are invited and copies of the bulletin are obtainable, free of charge, from: Dr. J. Annett, Department of Psychology, The University, Sheffield, 10.

Basic Human Factors for Engineers. By PAUL A. VERDIER. (Exposition Press Inc., New York. 1960) [Pp. 103.] $4.00.

DURING the past ten years there have been a number of reasonably successful attempts to reduce the findings of Ergonomics to a manual or cook-book from which the design or production engineer can obtain the information he requires without too much effort or background reading. This book is the first attempt to make a similar simplification of the principles and investigatory techniques. The author is described as an engineering psychoglogist but it emerges that he must be an engineer not inhibited by too close an acquaintance with experimental psychology. For example perception and sensation are distinguished in that "perception is the physiological function of the five groups of exteroceptive sense organs and cells" and "sensation is the awareness of changes occurring within the body". He separates human work into four different functions, the perceptual factor, the judgemental factor, the internal stress factor and the motor ability factor, produces an 'engineering definition' of each in about two lines and suggests that "the aforementioned four basic human factors are to provide the essential behavioural cornerstones out of which an entire theory of human engineering will be evolved".

In fact the major part of the book is devoted to the explanation of special abbreviations (hi.I.ps. means a high level internal psychological stress) and a range of check lists and analysis sheets which are intended for use in the study of men and tasks. One is reminded of Crossman's (1956)* Sensori-motor Process Chart with the difference that in this case there is little sign of the acute awareness of the theory of human skill which lay behind Crossman's work.

It is too easy to dismiss the author's approach as superficial and unimportant. The level and objectives are certainly very different from those of this journal but Dr. Verdier is, no doubt, a most successful practitioner and Ergonomics or Human Engineering is the study of man at work.

The book illustrates once again the tremendous gap between the industrial practitioner and the academic worker and the difficulties which have to be faced in attempting to combine within one subject a whole field of pursuit of knowledge and its commercial application.

W. T. SINGLETON.

Programmed Learning. A revolution in instruction. By D. A. COOK. Columbia University Graduate Faculties Newsletter. November, 1960. (Available on request from the author at Basic Systems Inc., 42 East 52nd Street, New York City).

THE paper describes an important innovation in the technology of instruction, widely referred to by the term 'teaching machines,' but more properly termed *programmed instruction*. The method rests upon the division of the subject-matter to be learned into a large number of very small steps, arranged in cumulative sequence. The contents of a course which might normally appear in a single textbook, would be presented in say 10 000 separate 'frames,' arranged in the proper order. Each frame introduces some new material, such as a definition, example, fact, or distinction, and ends by calling for a response on the part of the student—e.g. filling in a blank. After responding, the student is given the right answer before proceeding to the next frame. The method thus emphasizes (1) small steps, (2) active response, (3) immediate feedback, and (4) individualization of rate of progress. The importance of these features arises from the experimental analysis of learning in the work of Harvard psychologist B. F. Skinner. In addition to his research in this area, Skinner has also designed several models of machines suitable for presenting such instructional programmes. Some machines will keep a record of student errors—a datum of great importance in the revision of programmes, and also in the development of a scientific approach to programming. Research results suggest that the ideal of nearly errorless programmes may be attainable, so that the motivation to learn can be freed from its dependence upon the fear of failure. This possibility, as well as the individualization of learning, relief of the teacher from routine drudgery, and very rapid learning yielded by the method, has led to great interest in programmed instruction in American educational circles. Foundations, universities, and government research agencies are all sponsoring research and development in the field. A number of companies are developing programmes in academic and industrial subjects, often in connection with a publishing firm for distribution. Special development to serve the needs of underdeveloped countries is being explored, and the field is regarded as providing new sources of understanding about the nature of human knowledge. (2 refs.)

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* CROSSMAN E. R. F. W. (1956), *Research,* **9,** pp. 42–49.

Physics and Medicine of the Atmosphere and Space. Edited by O. O. Benson and H. Strughold. (London: John Wiley & Sons Inc., 1960.) [Pp. xxiii+645.] 100*s.*

This book is a well presented collection of papers given at the Second International Symposium of Physics and Medicine of the Atmosphere and Space. This meeting, held in San Antonio, Texas, took place in 1958—seven years after the first symposium.

Those who are already familiar with the collected papers of that first symposium, will find that the information contained in the present book is complementary to the earlier report. New information is presented, and new experimental techniques have been employed to verify earlier hypotheses.

The book, however, will disappoint the reader who looks for biological data obtained in orbital flights, for recovery techniques were not sufficiently developed when this conference was held. Experimental data on physical characteristics measured during such flights are however presented.

The value of the book to the interested physicist or biologist is that it weds the two disciplines. It also constitutes a unique source of reference on environmental factors to be encountered, and their effects on man.

Familiar subjects are re-examined in a new light, for example " In the first fifty years of human flight we were concerned with extreme *g*-forces, as they occur in crashes on the solid surface of the earth. Today we have the same problem, in a more complicated manner, when a vehicle hits the denser layers of the atmosphere on re-entry from space ".

T. C. D. Whiteside.

Accident Literature. World Health Organization. Washington. April, 1961.

The World Health Organization chose for the theme of its 1961 World Health Day campaign "Accidents Need not Happen ". For the guidance of the regional officers in the various co-operating countries a series of leaflets was issued covering safety in the home and factory and on the roads.

On the whole, the approach of these leaflets is sound. They refrain from just exhorting people to drive or work safely and give examples of how accidents can be avoided by good housekeeping, the development of safe methods of doing jobs and by training people to use these methods. Ergonomics and the safety aspects of the design of equipment are not, however, given attention. Although the campaign might help to reduce the liability of people to have accidents with equipment which they already own, it does not mention that a further reduction would be possible if consideration was given to man's limitations and capacities when equipment is being designed. For instance no mention is made of the need to consider population stereotypes when establishing the relationship between a control and its associated display. One of the most welcome features of the leaflet is the great emphasis placed on the importance of teaching people the safe way to work, drive, etc. It is also stressed that people should be aware of the risks which it is reasonable to take and those which it would be dangerous to take. The disadvantages of vague warnings which do not indicate the nature of the danger are noted. A plea is made for more research into ways of preventing accidents and the work of the Road Research Laboratory is given as an example of the way in which research can help.

R. G. Sell.

Human Factors in Jet and Space Travel. A medical-psychological analysis. Edited by S. B. SELLS and C. A. BERRY. (New York : Ronald Press Company, 1961.) [Pp. xvi+386.] $12.

THIS book covers at a rather elementary level, the ergonomics problems of flying and space travel. It thus appears to be aimed at a much wider audience than those directly connected with the field. The book is well printed, and well laid out with headings and subheadings. It is also easy to read, and many references are given for those wishing to go more thoroughly into particular points. After an introductory overview by Captain Ashton Graybiel, a member of the Executive Council of the Aerospace Medical Association, the next five chapters state the problems : what the environment is like, and what man is like. A chapter is included on group behaviour in flight, in which it is noted that the efficiency of a bomber crew is not necessarily related to " feelings of well-being and cohesion reflecting enjoyment of group participation ". Most of the remaining chapters describe how the problems are being tackled : selection, training, preventive medicine, flight safety, and the engineered environment of the space vehicle. The last two chapters on future space vehicles and space travel merge into science fiction.

Although probably the best single contribution, Chapter 11 fails to fit the pattern of the book, since half of it covers material discussed elsewhere. This problem of duplication has not been tackled as ruthlessly as it should have been by the editors of a volume covering a restricted field with 13 independent contributors. The reader should not be inflicted with three elementary and quite uncritical introductions to Effective Temperature. The first introduction gives the chart of the American Society of Heating, Refrigerating and Air Conditioning Engineers Inc. (Fig. 5–8, p. 108), but the following two introductions (pp. 208 and 245) fail to refer to this figure. Your reviewer feels that the space occupied by the latter two introductions could have been put to better use by explaining that effective temperature is *not* a very good predictor of either physiological or behavioural measures, since it underestimates the detrimental effect of damp heat. Some of the impression of duplication has to be blamed upon the publisher. In chapter 9 from pages 190 to 205 pairs of pages are interleaved with other pairs from chapter 11 ; 8 pages are completely missing while another 8 pages have been printed twice, the second time out of context. The book has presumably been rushed to catch the wave interest in the ergonomics of space travel before it breaks.

E. C. POULTON.

Management Control Systems. By MALCOLM and ROWE. (London : John Wiley & Sons, 1961.) [Pp. xiii+375.] 58*s*.

THIS book contains the proceedings of a symposium held at the System Development Corporation (S.D.C.) Santa Monica, California, in July 1959, and is the work of 22 contributors. S.D.C. is engaged in developing automated control systems for the U.S. Military and was anxious to pass on its experience with such large-scale military control systems as SAGE (Semi-Automated Ground Environment). A further reason for the symposium is given by the editors in the preface—" There is a distinct opportunity for innovation in management controls—an opportunity to make a quantum jump in the field to a *total* integrated system . . . Recognizing this, System Development Corporation decided to explore the possibility of developing an example of such a total system by creating a research project dedicated to the public interest. As part of this research, a necessary first task has been to develop a good appraisal of the state of the art of management controls."

Management control is an important subject as control difficulties are among the most influential factors in restricting company growth. This book, however, is uneven in its coverage of the subject and has more than its share of such linguistic conundrums as ' multi-dimensional utility measures '. It is mainly concerned with the potentialities of electronic data processing (E.D.P.) in the field of management control. It contains both authoritative opinion and case studies and can be recommended to those considering the application of E.D.P. to their own concerns.

Although each author has his own slant, there is much consistency of viewpoint. It is shown that if the full potential of the computer is to be realized, consideration must first be given to the informational needs of management and the information flow in the business. For example, it may be found that higher management is being supplied with detailed information on operations and functions, when their need is for information which merely shows deviations from plans. Similarly, it may be found that the organization structure of the business causes an uneconomical transfer of information. As one author puts it " too many controls are based on ease of measurement rather than need . . . There appears to be too much emphasis being placed on the rapid gathering and processing of information rather than the development of analytical and evaluating tools which can translate this data into a readily usable form ".

In fact most electronic computer application to date in the commercial field is no more than the mechanizing of existing clerical procedures to get information more quickly and/or reduce clerical costs. With such limited objectives, results have often been disappointing. It is generally agreed by the authors that " optimising components or parts of a system may lead to sub-optimising in the total system . . . A firm cannot operate as a series of uncorrelated organisations." There is a need to integrate controls. For example, there is a need in stock control to pay regard to the cash budget. However, several of the authors show the difficulty in the task of seeking a ' total integrated system '. The concept of integrating all of a company's controls into one index capable of showing optimum total performance remains an ideal. Much more research is needed into the decision-making process. Although electronic data processing can reduce the danger of sub-optimization by taking account of more variables in the business situation, it can only make decisions if the decision-making process can be formalized. The factors and areas to be considered for analysis and control, and the problems selected for solution will always remain a field for management judgment.

J. O'SHAUGHNESSY.

ERGONOMICS RESEARCH SOCIETY

Joint Meeting of the Ergonomics Research Society and
British Occupational Hygiene Society on

THE DESIGN AND USE OF RESPIRATORS

at Porton, July 5th and 6th, 1961

ABSTRACTS OF PAPERS

PROBLEMS IN THE DESIGN OF UNDERWATER BREATHING APPARATUS

By Commander J. R. Carr, O.B.E., A.M.I.E.E.
Royal Navy, Superintendent of Diving, Royal Navy

The problem in design of underwater breathing apparatus is to know exactly what is needed. Success depends on choosing a satisfactory compromise between conflicting considerations, the relative importance of which is not known, and then in obtaining the confidence of the user.

Man's lungs must be pressurized to the equivalent pressure of the surrounding water so that the mass of breathing gas needed to maintain respiration increases rapidly with depth. Thus the endurance required determines broadly the type of apparatus. Any prolonged operation necessitates a surface supply of gas; to be self-contained and make the maximum use of the gas carried involves a rebreathing system with its attendent complications; simplicity of operation is achieved with the demand valve and open circuit set.

Some effects of various gases on man under pressure are mentioned to indicate their influence on design. The importance of enabling man underwater to conform as closely as possible to his natural breathing pattern is stressed. The impracticability of relating the psychological and physiological hazards introduced by the limitations of the set directly to these limitations leads to an empirical approach.

The factors concerning the relationship of breathing resistance and gas flow are enumerated and the siting of the pressure control on the diver is described. The methods enforced by the need to dispose of exhaled carbon dioxide interfere with natural breathing. The effect of breathing a denser gas is considered and the degree of compensation possible within the set and the body is shown.

The operational and engineering problems of design are merely summarized in order that an illustration of all the choices made for a specific design can be given.

THE WORK OF VENTILATING RESPIRATORS

By E. A. Cooper
Department of Anaesthesia, Newcastle-upon-Tyne

The paper is devoted to a very general consideration of the resistance to breathing which is offered by respirators. These fall essentially into one of the main categories of simple air filter, or closed circuit. Both types offer resistance to breathing due to the movement of gases against frictional forces but different physical laws usually govern the relationship between the rates of flow and the necessary pressures. Furthermore, in the closed circuit respirator which has a rebreathing bag, additional resistance to expiration is offered by the elastic pressure due to the latter's distension.

The physiological effects of external resistance are considered in relation to the mechanics of respiration and cardiorespiratory function.

It is possible to correlate the behaviour of the two categories of respirator by assessing the rate of additional, external, respiratory work done against the resistance of the apparatus at known respiratory activities. Hence it is possible to suggest certain general standards of allowable resistance to respiration which may be applied to various types of respiratory protective devices.

PHYSIOLOGICAL ASPECTS OF RESPIRATOR DESIGN

By J. E. Cotes

Pneumoconiosis Research Unit of the Medical Research Council, Llandough Hospital, Nr. Penarth, Glam.

A respirator can be considered as an extension of the subject's own breathing apparatus and should have appropriate characteristics. It must connect comfortably without leaks and have resistance properties and deadspace appropriate to the wearer in the conditions in which the device is to be employed. The facepiece should come in a range of sizes and be individually fitted to accommodate the different distributions of face sizes of men and women and the changes with age. The use of a device which does not meet these requirements may lead to inhalation of toxic material as well as diminished physiological efficiency and exercise ability. Examples of difficulties which have arisen along these lines with oxygen masks and dust respirators are discussed.

As well as their protective properties, closed circuit respirators permit oxygen enrichment of the subject's inspired gas and its humidification and thermal regulation. In the event of failure they carry the risk of carbon dioxide accumulation and asphyxia. The design specification needs to be determined in the light of individual applications and the proportion of the population at risk for which the device is intended. In addition the policy on oxygen enrichment merits reconsideration: it is probably inadvisable to exceed a concentration of 50 per cent in normal circumstances.

PROTECTION AGAINST DUST

By R. G. Dorman

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Particles much larger than 10 μ are caught in the nose and, unless they are soluble and toxic, do not normally constitute a health hazard. The fibrous filter dust respirator must therefore be efficient in stopping smaller particles but, even so, it should be axiomatic that it is the last line of defence and that the real aim should be the prevention of dust from reaching the air which we breathe.

Except in the case of the resin-wool filter, which is electric in its action, the finer the fibres in the filter the more efficient it will be, but, in practice, larger fibres are incorporated to give strength and to prevent clumping of the finer. Large surface area, generally obtained by pleating, is also desirable to reduce air resistance, to limit particulate penetration, which usually increases with velocity, and also to provide a longer life before the filter becomes clogged. It is essential to ensure good fit of the facepiece and to maintain the expiratory valve in a satisfactory condition or leakage may outweigh protection given by the filter. A few results of leakage tests are quoted.

Data are presented to show how particulate penetration varies with particle size, indicating that the size most difficult to filter is about 0·3 μ equivalent diameter, larger particles being more easily caught by inertia and smaller ones by Brownian motion. An outline is given of the two particulate penetration test methods in use in Great Britain: the methylene blue test in which samples of the unfiltered and filtered clouds are impacted on esparto paper, and the intensities of the blue stains compared; and the more sensitive photo-electric sodium flame test in which the penetration of an aerosol of common salt is measured by means of flame photometry. Desirable standards of protection are also discussed.

PROBLEMS OF COMMUNICATION IN BREATHING EQUIPMENT

By J. Ernsting and J. E. Gabb
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Certain aspects of the problems of communication in breathing equipment, with particular reference to those introduced by the environment encountered in aviation, e.g. high noise levels and reduced barometric pressure, will be discussed. Techniques for assessing the noise, including properties of certain types of breathing equipment, are described. The effects of reduced barometric pressure and positive pressure breathing upon auditory acuity have been assessed and the results of these investigations are presented. It has been shown that speech gives rise to respiratory flow patterns which impose severe design requirements upon breathing equipment. The inspiratory flow patterns which are produced by speech have been measured and the results of these measurements are stated.

THE USE OF RESPIRATORS IN THE IRON AND STEEL INDUSTRY

By J. Graham Jones,
Richard Thomas and Baldwins Ltd.

The diversity of processes involved in the Iron and Steel Industry is shown under the broad classification of (*a*) production, processing and transportation of raw materials, (*b*) iron making, (*c*) steel making, (*d*) processing and finishing of iron or steel, (*e*) ancillary processes. The possible atmospheric contaminants from various processes are discussed. They may be particulate in the form of dusts, fumes, mists or smokes, or non-particulate in the form of vapours or gases. Their toxic effects vary according to the contaminant, its concentration and the length of exposure. Some could prove fatal in a very short time, others because of their long term effects. Some could produce occupational diseases of varying severity. Some could produce a general lowering in the standard of health and some could be merely unpleasant. Many of these contaminants are controlled at source, this is not possible in every case. It is, therefore, necessary to protect the workman in certain cases. Short-distance breathing apparatus, air-line masks supplied from compressors and self-contained compressed air apparatus are all required. Canister respirators have a very limited value but are still required in isolated situations. Dust respirators are required on a variety of jobs.

Two major problems requiring protection of the workman are discussed in more detail. The first, carbon monoxide, is considered with special reference to Blast Furnaces. The second, that of general dusty conditions, is sub-divided to refer to those substances capable of producing a definite occupational disease, and those which are not. Most of the dust problems in the industry are in the latter group and the respirator needs are considered in relation to the arduous and hot nature of the jobs to be performed.

THE USE OF RESPIRATORS FOR PROTECTION AGAINST AIRBORNE RADIOACTIVITY

By S. T. Hermiston,[†] R. F. Hounam,[‡] R. P. Rowlands[§]

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The paper illustrates the types of respirators and self-contained breathing apparatus in common use in the United Kingdom Atomic Energy Authority and describes practical experience of their large-scale use in industrial conditions. Reference is made to the operational problems of (i) securing adequate fit under factory conditions, (ii) comfort and vision, (iii) decontamination and monitoring.

The paper then describes performance characteristics required of an ideal respirator for atomic energy use. It emphasizes that in the design of a complete respirator the performances of the canister and the outlet valve, and the fit of the face-piece must be interrelated. The latter which is closely associated with the drill and discipline in the use of the respirator is currently of greatest interest. Results are presented showing the efficiency of a lightweight canister suitable for protection against airborne dusts and radioactive iodine vapour.

THE INFLUENCE OF RESPIRATORS ON TOLERANCE TO HEAT IN MINE RESCUE OPERATIONS

By F. Lavenne and P. Leyh

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A comparison was made between three closed-circuit respirators, two of them, the Draeger and the Fenzy, supplied with compressed oxygen, one, the Aerencheon, supplied with liquid air, also an open-circuit apparatus, the Air Magic, supplied with compressed air.

Two types of exercise at different levels of temperature were performed by nine rescuers wearing the different respirators. The inspired air temperature, the oral and rectal temperatures, the temperature of the skin, the heart rate, the blood pressure and the respiratory frequency, and the sweat loss were measured.

In all conditions the inspired air temperature was significantly higher in the Fenzy than in the other apparatus. The mean difference between the Fenzy and the two other closed-circuit respirators may reach 7 to 8°c. In this respect the Draeger seems slightly better than the Aerencheon for light work in very hot conditions, but slightly inferior for heavy work in less severe environments.

The inspired air temperature is less influenced by the type of gas (compressed oxygen or liquid air) than by the other characteristics of the circuit, particularly by the type of CO_2 absorber. Their design in all three respirators should be improved to lower the inspired air temperature.

Inspired air temperature has a small effect on body temperature, the differences observed between the Fenzy and the Aerencheon being statistically significant.

There was no correlation between the inspired air temperature and the other physiological variables. On the contrary, the heart rate was generally but not significantly lower with the Fenzy than with the Draeger. The lesser weight of the Fenzy seems to compensate for the high temperature of the inspired air.

The open circuit apparatus, with its cooler inspired air, should be used in preference to the other respirators tested when a source of compressed air is available.

THE LIMITATIONS OF GAS MASKS AND DUST MASKS AS MEANS OF PROTECTION AGAINST OCCUPATIONAL HAZARDS

By H. J. R. Letts

Chemical Defence Experimental Establishment, Porton Down.

Dust masks and canister masks (gas masks) are used to protect against dusts and gases or vapours and mists present in otherwise respirable atmospheres in a wide range of occupations. Although the legislation requiring approved respirators is limited and specific it exerts an indirect influence on the design—as distinct from the manner of use—of these devices in all relevant occupations in which compensation claims are possible. The essential control standards maintained by the delegated authorities—The Factory Inspectorate and the Ministries of Agriculture and Power—are based on a normal canister requirement for complete absorption of a 1 per cent volume concentration for 30 min or a maximum allowable particulate filter penetration of 10 per cent of a methylene blue cloud of approximately $0{\cdot}3\,\mu$ particles. Available respirators meet these requirements without difficulty. Data on absorbent and filter performance is extensive. Dangers due to intrinsic limitations are not serious and can be minimized by correct codes of practice. In contrast the overall protection of worn respirators is controlled by the variability and unpredictability of the face seal. Quantitative measurements are difficult and data is limited. Measurements on men at rest and performing simple exercises whilst wearing typical dust (half mask) and canister respirators in bacterial spores indicate a significant leakage incidence at the 10 per cent level. Wearability is an important aspect of overall protection owing to the tendency to avoid discomfort. Inhibition of evaporation and reduced heat loss at the fitting surface may be comfort controlling factors. Gas and dust masks should be used as the last protective resort and may be dangerously inadequate when worn for long periods against insidious hazards. Present designs are directly or indirectly based on data from military sources. Future significant improvements derived from service experience are not anticipated. Air supplied devices based on existing mask designs could provide safe, predictable and comfortable protection. Initiative from users would be necessary to stimulate the design by appliance manufacturers of compact and portable electrically-driven individual filtration units.

PROTECTION AGAINST TOXIC VAPOURS

By F. A. P. Maggs

Chemistry Research Division, Chemical Defence Experimental Establishment, Porton Down.

An outline is given of the methods of testing respirator containers for protection against vapour or gaseous hazards and some general considerations are discussed relating to the mode of action of the adsorption from an air stream.

OBSERVATIONS ON THE MANUFACTURE AND TESTING OF RESPIRATORS

By A. C. Peacock

Chemical Defence Experimental Establishment, Porton Down.

The requirements for manufacture of a uniform product which will ensure protection of the user are discussed.

The relative merits of mechanized and manual methods of production and assembly in relation to cost are compared. Mechanical methods are more easily controlled and hence can more easily ensure a uniform product than manual methods, besides involving lower inspection costs.

The choice between the two methods will be influenced by the volume of output, since the cost of mechanization may be unwarranted for small production.

It is suggested that it would be of advantage to industry if the number of designs of respirators for industrial use were limited and production undertaken by a single organization.

RESPIRATORS FOR USE IN MINES

By C. R. Senneck

Safety in Mines Research Establishment

The breathing apparatus used in mine rescue and recovery operations are almost exclusively of the two-hour closed-circuit type. Desirable performance standards and operational requirements for such apparatus are briefly considered. Assuming leak tightness and an adequate chemical performance, some of the most important requirements are that the apparatus should not add to its wearers' heat load, that it should be of low resistance and low weight, and that its operation should be automatic. The two standard types of mine rescue breathing apparatus have had long histories of successful use, but each has undesirable characteristics which it should be possible to avoid in new designs.

A newly-developed closed-circuit liquid-oxygen set is described. This apparatus, known as SIMBAL (Safety in Mines Breathing Appliance : Liquid), was designed primarily to provide cool, reasonably dry inspired air since the thermal stress on mine rescue personnel is often severe and is increased by existing types of closed-circuit apparatus. Fully charged with $5\frac{1}{2}$ lb of liquid oxygen, SIMBAL weighs 33 lb. It will normally provide inspired air at below ambient temperature for over two hours. During heavy work in an ambient temperature of 90°F, the rate of respiratory cooling is about 1 kcal/min. SIMBAL's resistance is about one third of that of the two standard types of apparatus, largely because of a new soda-lime canister which has a resistance of only 1 cm of water at 300 l./min. Once the set has been filled, its operation is entirely automatic.

ERGONOMICS OF THE RESPIRATOR

By R. J. Shephard

Chemical Defence Experimental Establishment, Porton Down.

Demonstration that performance is adversely affected by the wearing of a modern service respirator is not easy, partly because improvements in design have reduced the restrictions placed on the subject, and partly because of the considerable reserve capacity and great adaptability of most body functions.

Overall psychomotor performance, as measured by a battery of psychomotor tests (light and heavy pursuit meters, ball-bearing picking and bolt-threading tasks) shows a slight (2–10 per cent) and in most cases statistically unsignificant decrement. Maximum physical capacity on a bicycle ergometer task is reduced by <4 per cent, and unpaced performance on an obstacle course by <9 per cent.

Deterioration in specific functions is also slight. Although there is some restriction of the visual field and loss of binocular vision, the subject learns to compensate by increased head-movement. Performance of visual tasks such as map reading is normal, although there may be a significant reduction of peripheral awareness.

Restriction of sweating under hot conditions imposes an added heat load of 0·2 kcal/min. This is less than 4 per cent of the metabolic cost of rapid walking, and accumulation of sweat is more significant as a source of discomfort than as a thermal hazard.

The added dead space of the respirator (<400 ml) and the resistance of the inspiratory canister (<10 cm H_2O at 100 l./min steady flow) each increase the respiratory load by some 50 per cent of the control valve during maximum effort on the bicycle ergometer. However, the energy expenditure involved (<6 w) is small relative to maximum effort (150 w).

Cardiac output, as indicated by the ballistocardiogram, is unchanged by prolonged respiration through an inspiratory resistance. However, both systolic and diastolic blood pressures show a modest increase, possibly attributable to hyperventilation. There is no change of pulmonary resistance (interrupter valve) after such an experiment.

Formal tests of sound transmission show moderate attenuation, mainly of higher frequencies, but distortion of speech is sufficient to increase the incidence of mistakes in intepretation of single words by 30–50 per cent.

The main factor limiting prolonged wear of the respirator is undoubtedly general discomfort, and tolerance is thus determined largely by training and necessity.

BREATHING APPARATUS IN THE BRITISH FIRE SERVICE

By F. C. S. Shirling

Home Office, Horseferry House, London, S.W.1

The British Fire Service uses self-contained breathing apparatus for fire-fighting. Respirators are not used because under fire-fighting conditions there is frequently an oxygen deficiency.

The types of apparatus used by Fire Brigades are the ‘ Proto ’ (one hour), the ‘ Salvus ’ and compressed air sets with a nominal duration of about 30 min.

Compressed air sets are favoured because they are simple, easy to maintain, cheap to run and the air is cool to breathe. Their great disadvantage is their poor duration/weight ratio. Although a nominal half-hour duration is considered acceptable in many of the smaller Brigades, the larger Brigades, particularly those with serious basement and shipping risks, consider a set of one hour's duration to be essential.

The chief disadvantage of ' Proto ' sets lies in the heat content of the inhaled oxygen after the set has been worn for a comparatively short time under hot conditions. In this respect some improvement is badly needed and it is perhaps for reconsideration whether there is some better alternative to soda-lime as a CO_2 absorbent. Liquid oxygen sets offer a possible solution except that breathing apparatus in Fire Brigades is required to be ready for immediate use.

Another important Fire Service requirement for breathing apparatus wearers is efficient means of communication between members of a team and between the scene of operations and an outside control point. We have, in recent years, been enlisting the co-operation of manufacturers to develop face masks with speech diaphragms for use with oxygen as well as compressed-air apparatus. These masks solve the problem of communication between wearers. For communication between the scene of the fire and the outside control we consider the answer to be telephone communications and experiments with this type of equipment are at present in hand.

HISTORY OF RESPIRATORS

By C. G. Trotman

Chemical Defence Experimental Establishment, Porton.

Respirators are classified into two general types—dust respirators (dust masks) and canister respirators (gas masks). Of the two types, dust masks are historically much the elder, but their history did not really commence until a performance standard was established in 1933 as a result of an extensive study of industrial dusts which was conducted on behalf of the Medical Research Council. It was found that the finer dust particles, which were known to cause pulmonary disease, were present to greater extent than had been thought, and that much more efficient dust masks than any which were then available were necessary for protection.

To meet the immediate need for an efficient design, the D.S.I.R. sponsored an official project which resulted in the Dust Respirator Mk IV. This was the predominant approved design for many years, but there are now a number of approved commercial designs which meet the performance standard.

The development of canister respirators for industrial use commenced seriously soon after World War I, largely as a result of the intensive research which had been carried out on war protection against poison gas. Chemical Works Regulations (1922) made the provision of respirators mandatory for certain industrial operations and laid down standards of performance required of respirators submitted for approval. Subsequently, procedures for testing the safety of industrial atmospheres were standardized, and codified methods of testing respirator canisters for their efficiency against a wide range of industrial gases and vapours were established. Commercial designs of canister respirators are now available for protection against most known industrial and agricultural hazards.

THE RESPIRATOR IN PHYSIOLOGICAL RESEARCH

By H. Wolff

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Almost any physiological measuring procedure requires that the measuring and recording apparatus should have some physical connection to the subject. This connection may take the form of a thermocouple, cardiac catheter, stomach tube, rectal thermometer, or a mask, to quote a few examples. The acceptability of the procedure, particularly when large numbers of unmotivated experimental subjects are involved, depends almost entirely on this link between subject and apparatus. In respiratory research involving the investigation of some parameter of inspired air and expired air, this matching component has ranged from a simple tube through mouth pieces and masks, to the ‘ space helmet ’. The use of masks has been almost universal when measurements have to be made over periods of more than 30 min ; their most frequent use in physiological research has been in the field of indirect calorimetry. Masks must be of low resistance both on inspiration and expiration, and must direct the inward air flow in such a way as to cool the face. For low levels of energy expenditure the problem is to avoid leaks around the edges of the mask without having to pull it close to the face to an uncomfortable extent. It should also be possible to talk intelligibly whilst wearing a mask and, if possible, to drink. However perfect a mask is it is still of low social acceptability and means are now being considered of obtaining information on ventilation volumes and energy expenditure without their use. This has become necessary because it is the intention to extend physiological research to members of an ordinary population living their ordinary lives. Specialized forms of masks, more analogous to space helmets in so far as they contain rather than cover the whole head, have been designed for studies on sleeping subjects and on small children. Mention will also be made of various measuring devices which have been attached to masks.

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